



(12) **United States Patent**
Sharma et al.

(10) **Patent No.:** **US 11,455,031 B1**
(45) **Date of Patent:** **Sep. 27, 2022**

(54) **IN-FIELD ILLUMINATION FOR EYE TRACKING**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 25 days.

(21) Appl. No.: **15/997,473**

(22) Filed: **Jun. 4, 2018**

(51) **Int. Cl.**
G06F 3/01 (2006.01)
H04N 5/225 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC **G06F 3/013** (2013.01); **G02B 19/009** (2013.01); **G02B 19/0009** (2013.01); **H04N 5/2256** (2013.01); **G02B 27/0172** (2013.01); **G02B 2027/0138** (2013.01); **G02B 2027/0178** (2013.01)

(58) **Field of Classification Search**
CPC G06F 3/013; G06F 3/011; G06F 3/044; G06F 3/04847; G06F 2203/0339; G06F 2203/04108; G02B 19/009; G02B 2027/0138; G02B 2027/0178; G02B 27/0172; G02B 19/0009;
(Continued)

(56) **References Cited**
U.S. PATENT DOCUMENTS
5,815,741 A 9/1998 Okuyama et al.
6,064,752 A 5/2000 Rozmus et al.
(Continued)

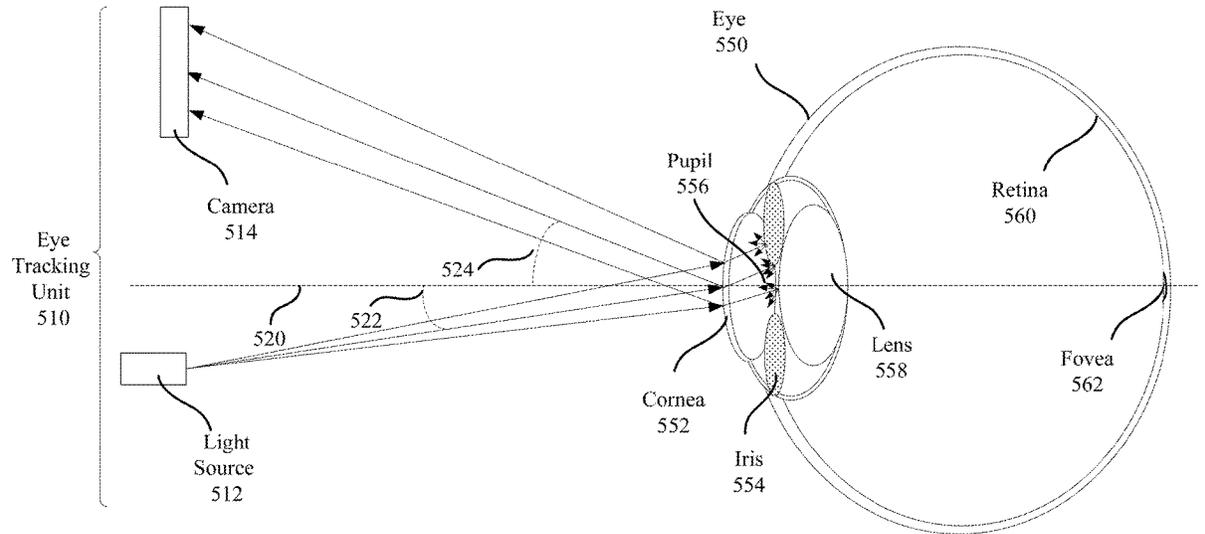
FOREIGN PATENT DOCUMENTS
CN 112470163 A 3/2021
EP 3797376 A1 3/2021
WO 2019226187 11/2019

OTHER PUBLICATIONS
U.S. Appl. No. 16/033,099, "Non-Final Office Action", dated Oct. 15, 2019, 11 pages.
(Continued)

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(57) **ABSTRACT**
Disclosed herein are techniques for eye illumination for eye position tracking. An illuminator for eye tracking includes a substrate configured to be placed in front of an eye of a user and a light source positioned on a surface of the substrate. The light source is configured to be positioned within a field of view of the eye of the user. A maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 μm.

20 Claims, 12 Drawing Sheets



- (51) **Int. Cl.**
G02B 19/00 (2006.01)
G02B 27/01 (2006.01)
- (58) **Field of Classification Search**
 CPC G02B 2027/0118; H04N 5/2256; G09G
 5/10; G09G 2320/0626; G09G 2354/00
 See application file for complete search history.
- 2017/0316264 A1 11/2017 Gustafsson et al.
 2018/0020137 A1 1/2018 Engwall et al.
 2018/0136471 A1 5/2018 Miller et al.
 2018/0196265 A1* 7/2018 Bouchier G03H 1/2294
 2018/0292896 A1* 10/2018 Hicks G09G 5/391
 2019/0025930 A1 1/2019 Fransson et al.
 2019/0265478 A1* 8/2019 Cok G06T 19/006
 2019/0361523 A1 11/2019 Sharma et al.
 2020/0355929 A1 11/2020 Zhang et al.
 2020/0379561 A1 12/2020 Sharma et al.

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,354,504 B1* 3/2002 Sabourault G06K 7/10732
 235/454
 7,519,287 B2 4/2009 Mok et al.
 9,335,548 B1 5/2016 Cakmakci et al.
 9,759,913 B2 9/2017 Saarikko et al.
 10,495,879 B1* 12/2019 Ahuja G02B 27/0172
 10,788,892 B2 9/2020 Sharma et al.
 2010/0188638 A1 7/2010 Eberl et al.
 2012/0228646 A1 9/2012 Kuo et al.
 2013/0099675 A1 4/2013 Ma et al.
 2013/0114850 A1* 5/2013 Publicover G06K 9/00604
 382/103
 2014/0340390 A1* 11/2014 Lanman H04N 13/344
 345/419
 2014/0375789 A1* 12/2014 Lou G02B 27/0172
 348/78
 2015/0097947 A1* 4/2015 Hudman G01S 17/89
 348/136
 2015/0177514 A1* 6/2015 Maimone G02B 27/0101
 345/8
 2015/0310670 A1 10/2015 Grossinger
 2016/0019715 A1 1/2016 Haddick et al.
 2016/0119612 A1 4/2016 Wu et al.
 2016/0249801 A1 9/2016 Gao
 2016/0352071 A1* 12/2016 Hogan H01S 5/40
 2017/0138571 A1 5/2017 Chen
 2017/0147859 A1 5/2017 Zhang et al.
 2017/0242161 A1* 8/2017 Zhang G09G 3/3406

OTHER PUBLICATIONS

International Application No. PCT/US2018/041842, "International Search Report and Written Opinion", dated Feb. 15, 2019, 11 pages.
 U.S. Appl. No. 16/033,099, "Advisory Action", dated Mar. 25, 2020, 3 pages.
 U.S. Appl. No. 16/033,099, "Notice of Allowance", dated May 20, 2020, 5 pages.
 U.S. Appl. No. 16/033,099, "Final Office Action", dated Jan. 27, 2020, 12 pages.
 U.S. Non-Final Office Action dated May 24, 2021 in U.S. Appl. No. 16/998,952.
 EP Application No. 18919754.4, "Extended European Search Report", dated Jun. 9, 2021, 9 pages.
 Final Office Action dated Oct. 8, 2021 for U.S. Appl. No. 16/998,952, filed Aug. 20, 2020, 14 pages.
 Final Office Action dated Jun. 13, 2022 for U.S. Appl. No. 16/854,667, filed Apr. 21, 2020, 16 pages.
 Li Z., et al., "Volume Holographic Spectral Imaging," Proceedings of SPIE—The International Society for Optical Engineering, 2005, 8 pages.
 Non Final Office Action dated Mar. 4, 2022 for U.S. Appl. No. 16/854,667, filed Apr. 21, 2020, 14 pages.
 Notice of Allowance dated Jan. 27, 2022 for U.S. Appl. No. 16/998,952, filed Aug. 20, 2020, 5 pages.
 PCT Application No. PCT/US18/41842, "International Preliminary Report of Patentability", dated Nov. 24, 2020, 7 pages.

* cited by examiner

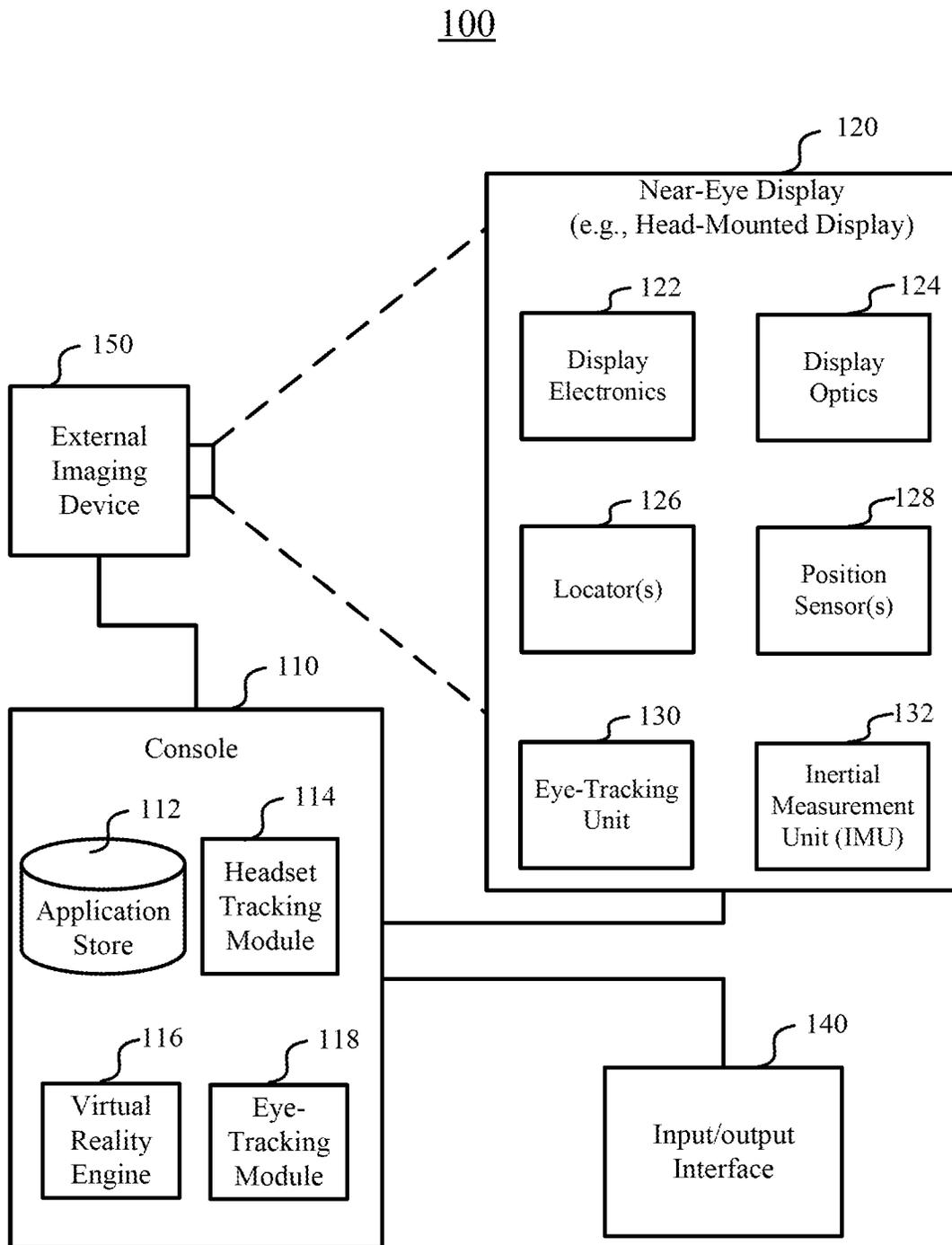


FIG. 1

200

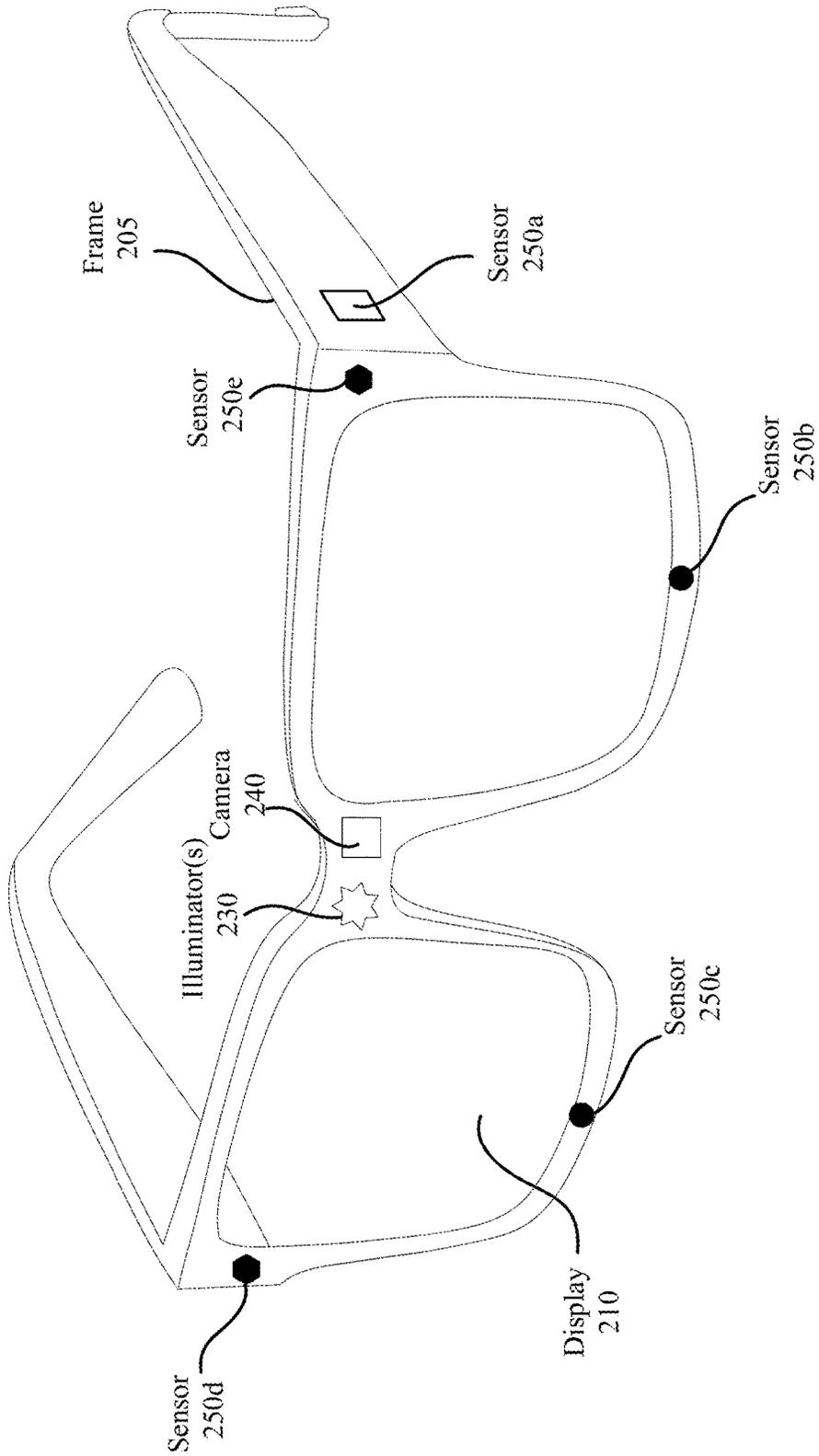


FIG. 2

300

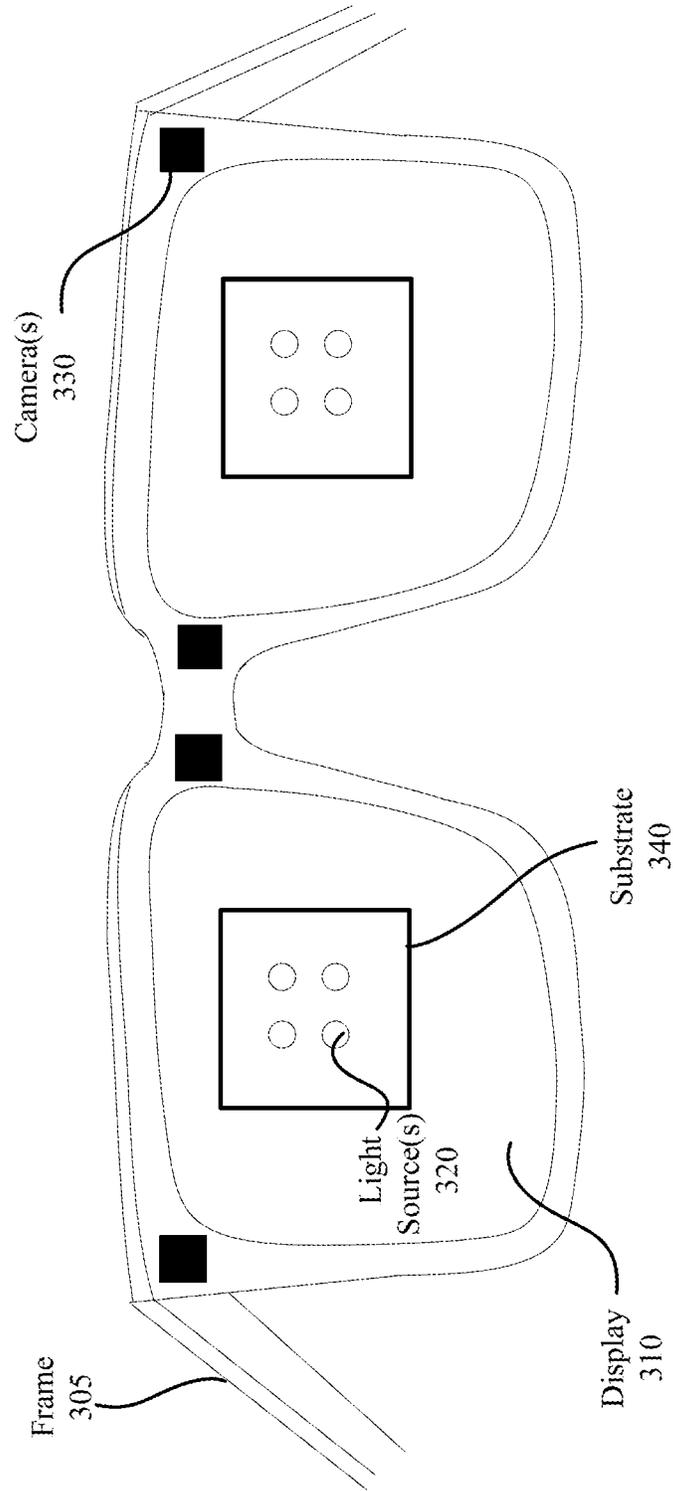


FIG. 3

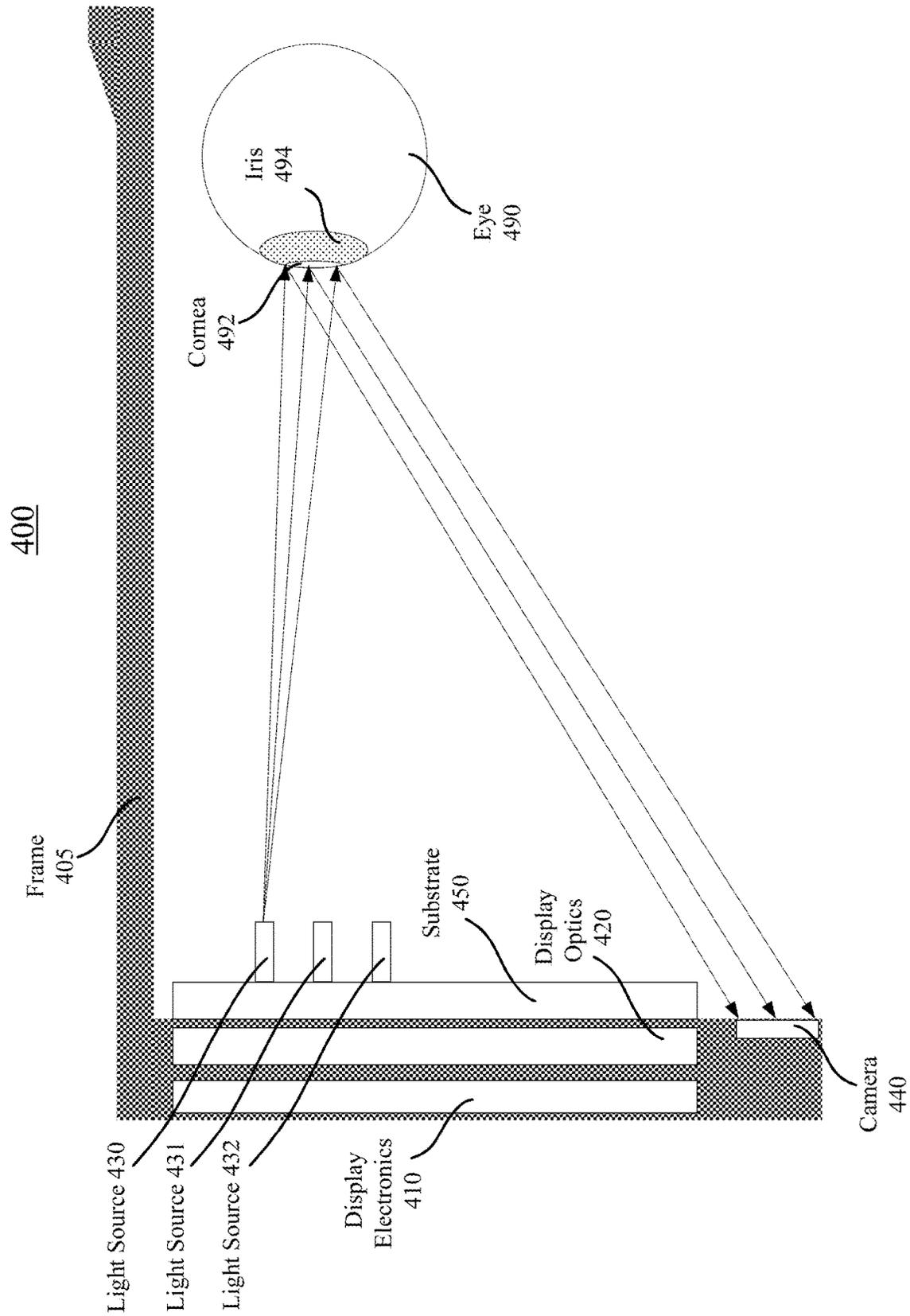


FIG. 4

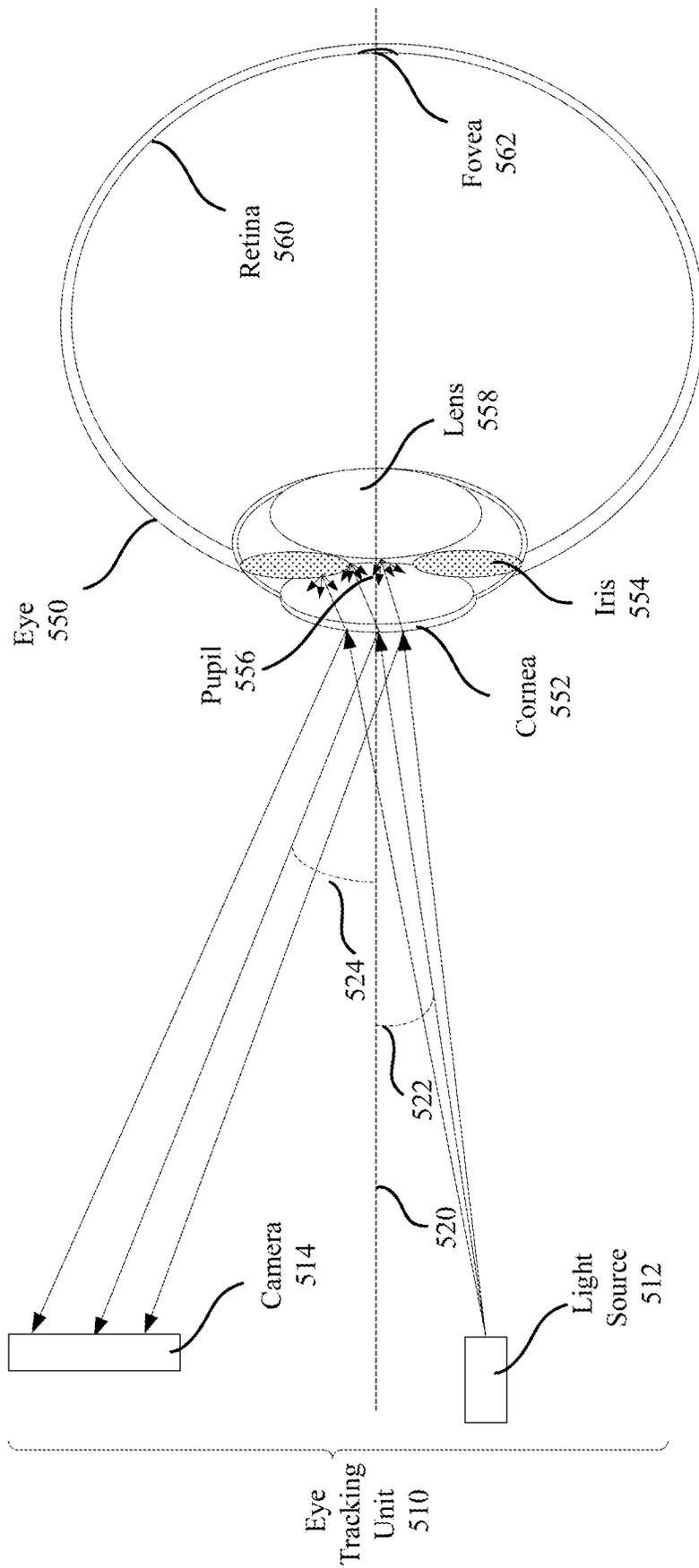


FIG. 5

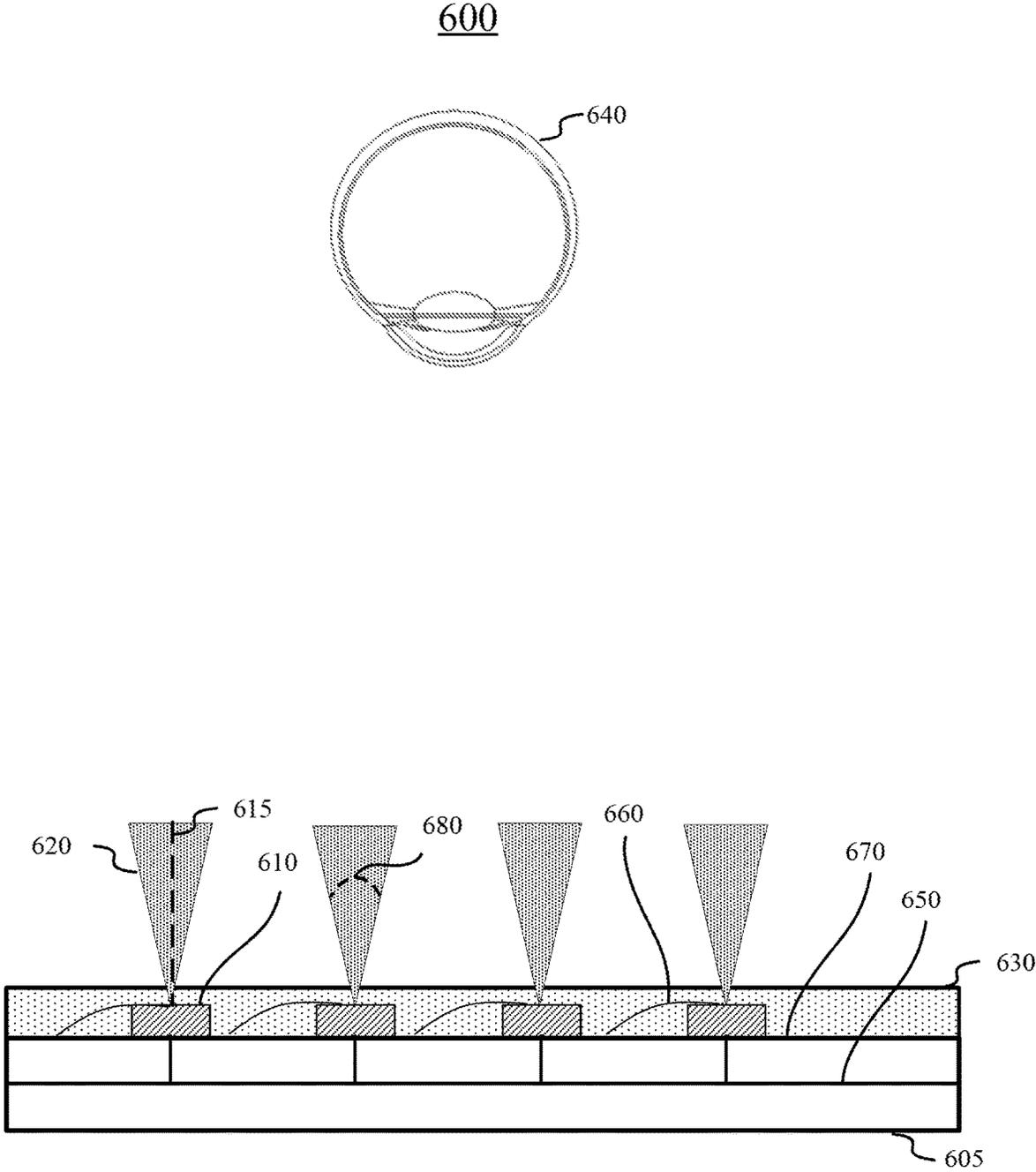


FIG. 6

700

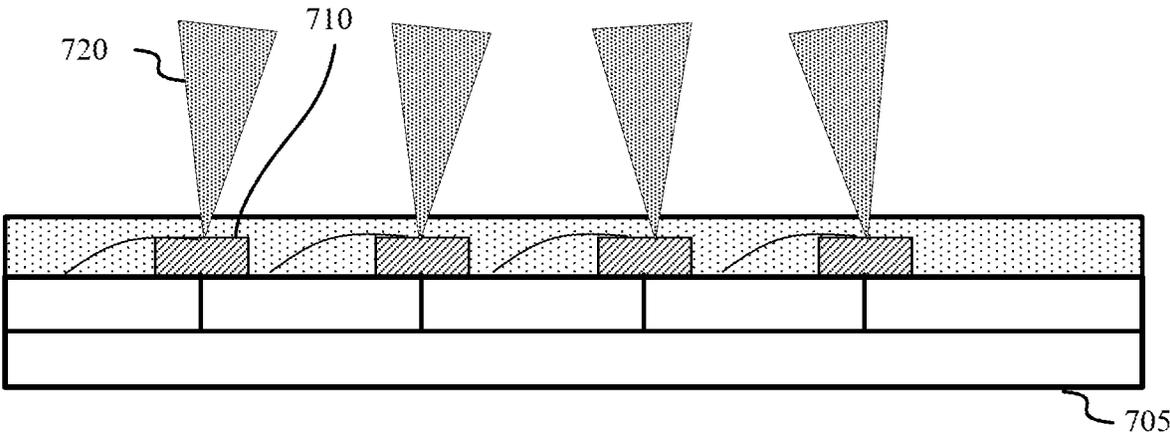
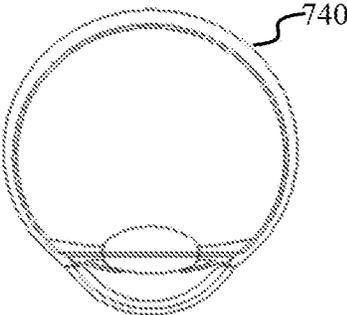


FIG. 7

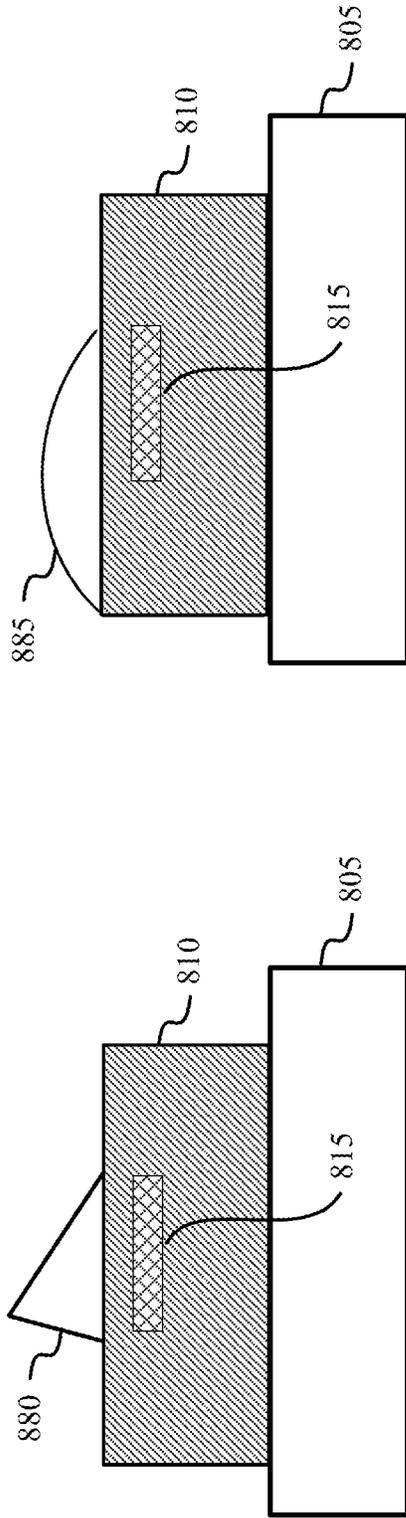


FIG. 8B

FIG. 8A

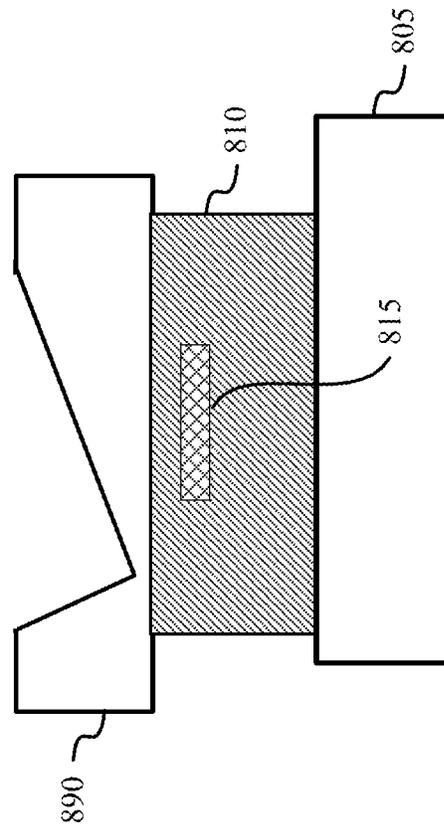


FIG. 8C

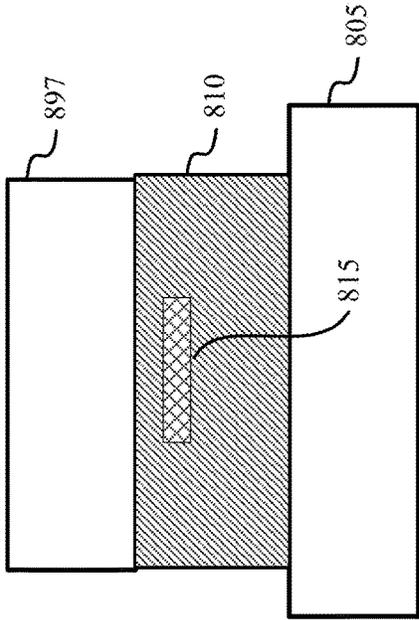


FIG. 8E

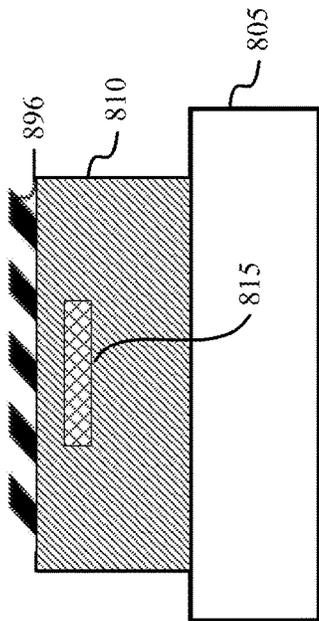


FIG. 8D

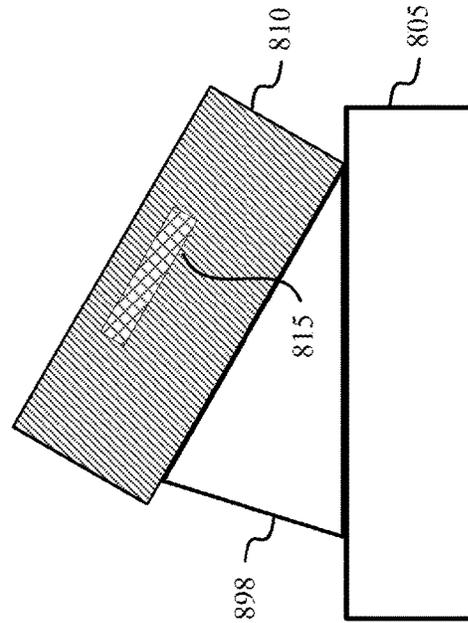


FIG. 8F

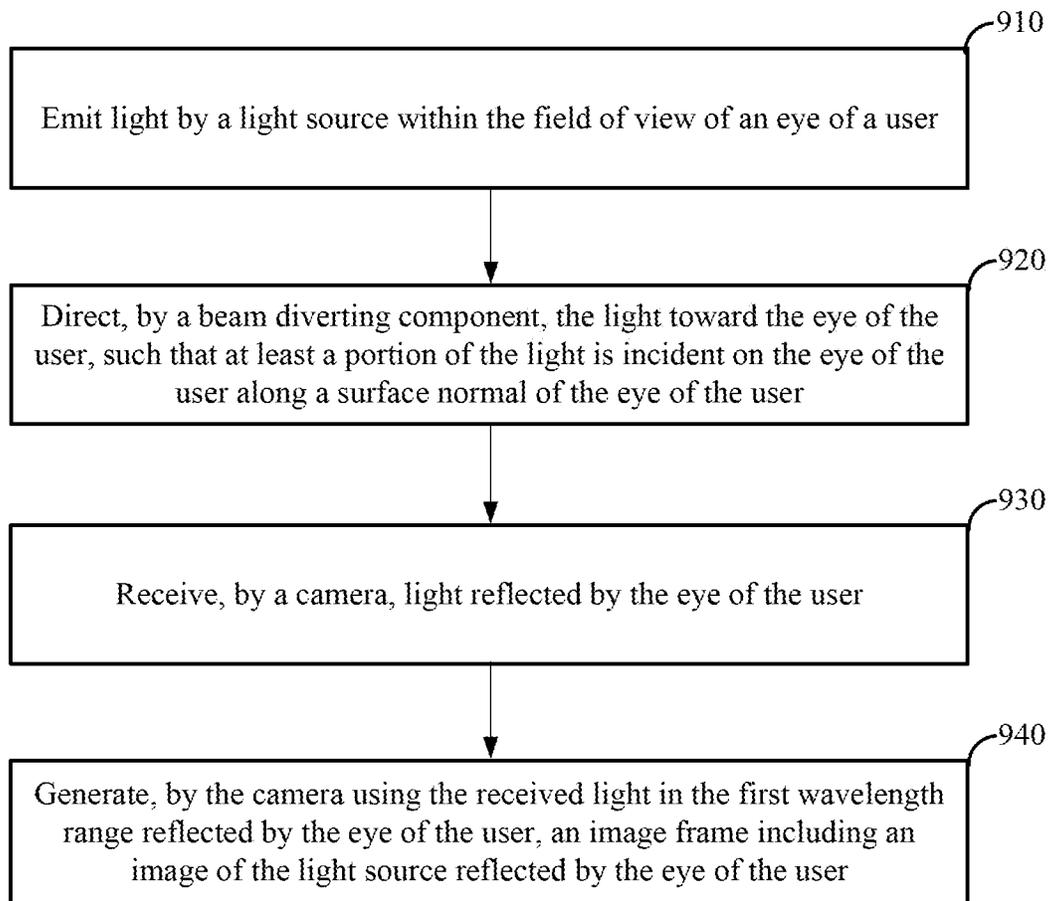
900

FIG. 9

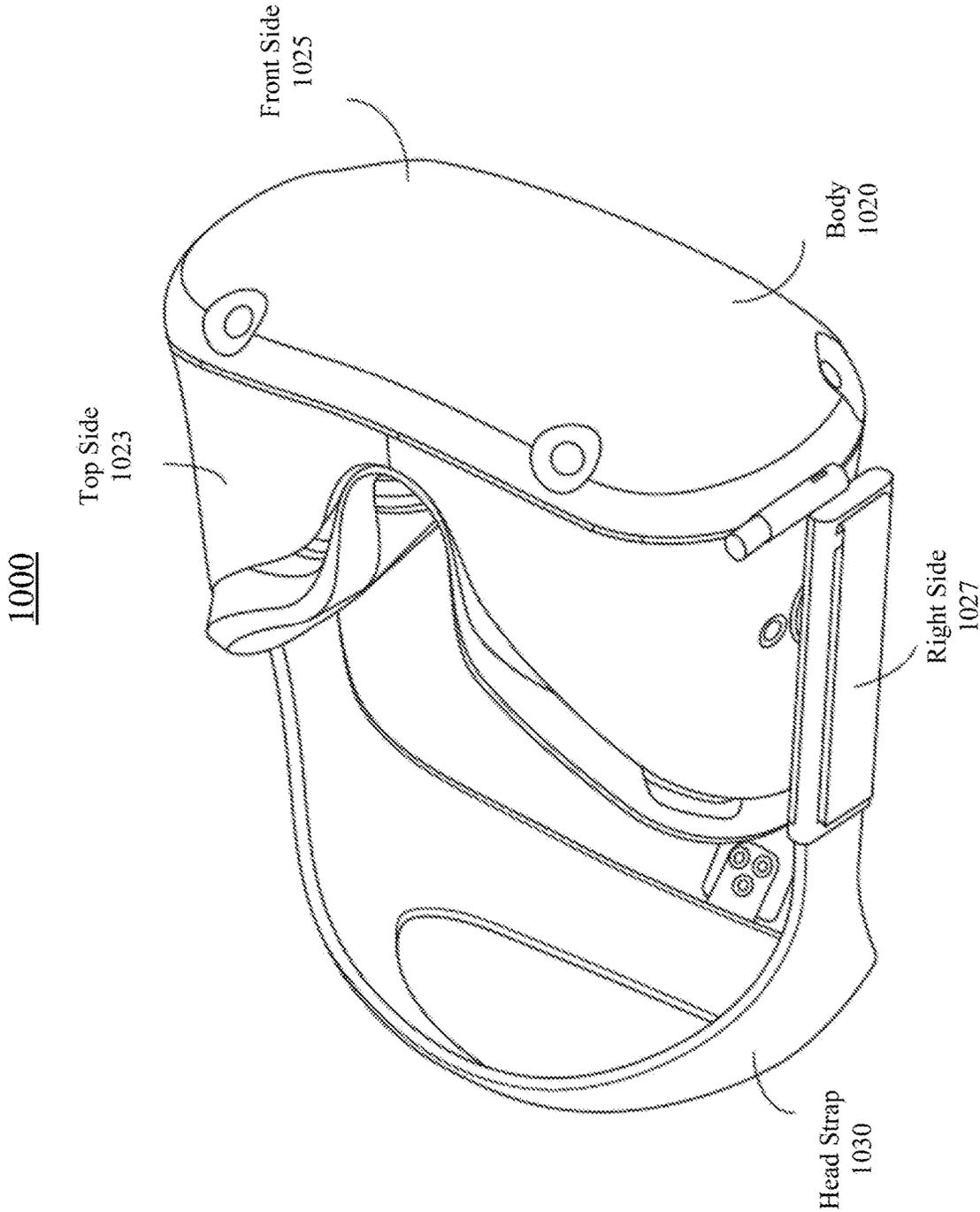


FIG. 10

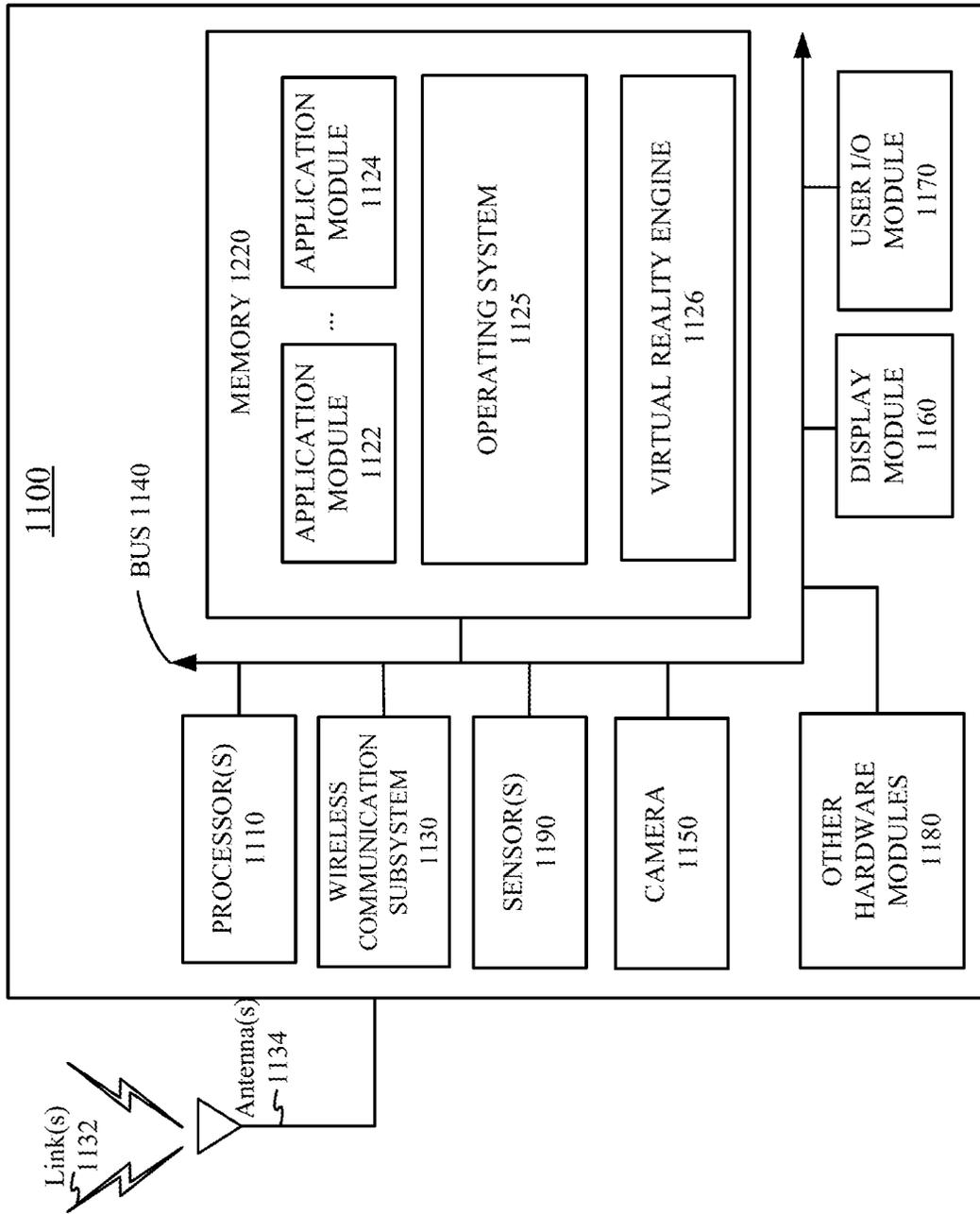


FIG. 11

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IN-FIELD ILLUMINATION FOR EYE TRACKING

BACKGROUND

An artificial reality system generally includes a display panel configured to present artificial images that depict objects in a virtual environment. The display panel may display virtual objects or combine real objects with virtual objects, as in virtual reality (VR), augmented reality (AR), or mixed reality (MR) applications. To interact with the artificial reality system, a user may need to provide inputs directed to at least a portion of the displayed image. Some artificial reality systems may include a dedicated input/output interface for receiving user inputs, such as hand and/or finger movements. However, traditional input/output interfaces may require frequent and active user inputs, and thus may prevent the user from having a fully immersive experience in the artificial reality environment.

An eye-tracking system can track the gaze of an artificial reality (e.g., VR/AR/MR) system so that the artificial reality system knows where the user is looking, and thus can provide a more immersive interface than a typical input/output interface predominantly reliant on a handheld peripheral input/output device. Eye-tracking may also be used for foveated imaging, foveated transmission of image data, alertness monitoring, etc. Existing eye-tracking systems may use light sources (e.g., infrared light) positioned at the periphery of the user's field of view to illuminate the eye, where the light illuminating the eye may be reflected specularly by the cornea of the user's eye, resulting in "glints" in a captured image of the eye. The position (e.g., gaze direction or rotation position) of the eye may be determined based on, for example, the location of the glints relative to a known feature of the eye (e.g., center of the pupil) in the captured image.

There may be several issues associated with existing eye tracking technologies. One of the issues is the size of the glints in the captured image for a light source that may not be a "point source." For example, an LED which may be used as the light source may have an emission area with a diameter of 200 μm or more. Thus, when the whole LED emission area is captured, the glint may not appear as a point in the captured image. Consequently, the center location of the glint in the image may not be precisely determined, and the errors in the approximation may lead to errors in the eye tracking result. In addition, the peripheral location of the light sources may negatively impact the accuracy of the eye tracking due to, for example, the large angles of the illuminating light from the light sources to the eye.

SUMMARY

The present disclosure generally relates to eye tracking in near-eye display devices. In some embodiments, an illuminator for eye tracking is provided. The illuminator includes a substrate configured to be placed in front of an eye of a user and a light source positioned on a surface of the substrate. The light source is configured to be positioned within a field of view of the eye of the user. A maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 μm .

An angle of an emission cone of the light from the light source may be less than 30°. The illuminator may also include a beam diverting component configured to direct light from the light source toward the eye of the user, such that at least a portion of the light is incident on the eye of the

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user at an angle with respect to a vector that is normal to a surface of the eye of the user. The beam diverting component may be a micro-prism, an inverse micro-prism, an off-axis micro-lens, a grating, or an inclined plane.

The illuminator may also include an encapsulation layer that surrounds the light source. A refractive index of the encapsulation layer matches a refractive index of the substrate. The substrate may include a conductive trace, and the light source may include an electrode that is electrically connected to the conductive trace. The illuminator may include a metal-loaded conductive adhesive that bonds the light source to the substrate.

The surface of the substrate may be flat. The substrate may include glass, quartz, plastic, polymer, ceramic, and/or crystal.

In some embodiments, an eye-tracking unit for a near-eye display device is provided. The eye-tracking unit includes a substrate configured to be placed in front of an eye of a user, a light source positioned on a surface of the substrate, and a camera configured to receive the light from the light source that is reflected by the eye of the user. The light source is configured to be positioned within a field of view of the eye of the user. A maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 μm .

An angle of an emission cone of the light from the light source may be less than 30°. The illuminator may also include a beam diverting component configured to direct light from the light source toward the eye of the user, such that at least a portion of the light is incident on the eye of the user at an angle with respect to a vector that is normal to a surface of the eye of the user. The beam diverting component may be a micro-prism, an inverse micro-prism, an off-axis micro-lens, a grating, or an inclined plane.

The illuminator may also include an encapsulation layer that surrounds the light source. A refractive index of the encapsulation layer matches a refractive index of the substrate. The substrate may include a conductive trace, and the light source may include an electrode that is electrically connected to the conductive trace. The illuminator may include a metal-loaded conductive adhesive that bonds the light source to the substrate.

The surface of the substrate may be flat. The substrate may include glass, quartz, plastic, polymer, ceramic, and/or crystal.

In some embodiments, a method of tracking an eye of a user of a near-eye display is provided. The method includes emitting light by a light source within a field of view of the eye of the user. A maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 μm . The method also includes directing, by a beam diverting component, the light toward the eye of the user, such that at least a portion of the light is incident on the eye of the user at an angle with respect to a vector that is normal to a surface of the eye of the user. Further, the method includes receiving, by a camera, light reflected by the eye of the user. The method may also include generating, by the camera using the received light reflected by the eye of the user, an image frame including an image of the light source reflected by the eye of the user.

This summary is neither intended to identify key or essential features of the claimed subject matter, nor is it intended to be used in isolation to determine the scope of the claimed subject matter. The subject matter should be understood by reference to appropriate portions of the entire specification of this disclosure, any or all drawings, and each claim. The foregoing, together with other features and

examples, will be described in more detail below in the following specification, claims, and accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Illustrative embodiments are described in detail below with reference to the following figures:

FIG. 1 is a simplified block diagram of an example artificial reality system environment including a near-eye display, according to certain embodiments;

FIG. 2 is a perspective view of a simplified example near-eye display including various sensors;

FIG. 3 is a perspective view of a simplified example near-eye display including an example eye-tracking unit;

FIG. 4 is a cross-sectional view of an example near-eye display including an example eye-tracking unit;

FIG. 5 illustrates light reflections and diffusions by an eye during eye tracking;

FIG. 6 is a simplified diagram of an example illuminator for eye tracking in an example near-eye display, according to certain embodiments;

FIG. 7 is a simplified diagram illustrating an example illuminator for eye tracking in an example near-eye display, according to certain embodiments;

FIG. 8A illustrates an example illuminator for eye tracking having a beam diverting component that is a micro-prism, according to certain embodiments;

FIG. 8B illustrates an example illuminator for eye tracking having a beam diverting component that is an off-axis micro-lens, according to certain embodiments;

FIG. 8C illustrates an example illuminator for eye tracking having a beam diverting component that is an inverse micro-prism, according to certain embodiments;

FIGS. 8D and 8E illustrate example illuminators for eye tracking having beam diverting components that are gratings, according to certain embodiments;

FIG. 8F illustrates an example illuminator for eye tracking having a beam diverting component that is an inclined plane, according to certain embodiments;

FIG. 9 is a flow chart illustrating an example method of eye illumination for eye tracking in a near-eye display, according to certain embodiments;

FIG. 10 is a perspective view of an example near-eye display in the form of a head-mounted display (HMD) device for implementing some of the examples disclosed herein; and

FIG. 11 is a simplified block diagram of an example electronic system of an example near-eye display for implementing some of the examples disclosed herein.

DETAILED DESCRIPTION

In the following description, for the purposes of explanation, specific details are set forth in order to provide a thorough understanding of examples of the disclosure. However, it will be apparent that various examples may be practiced without these specific details. For example, devices, systems, structures, assemblies, methods, and other components may be shown as components in block diagram form in order not to obscure the examples in unnecessary detail. In other instances, well-known devices, processes, systems, structures, and techniques may be shown without necessary detail in order to avoid obscuring the examples. The figures and description are not intended to be restrictive. The terms and expressions that have been employed in this disclosure are used as terms of description and not of

limitation, and there is no intention in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof.

As used herein, visible light may refer to light with a wavelength between about 400 nm and about 750 nm. Near infrared (NIR) light may refer to light with a wavelength between about 750 nm and about 2500 nm. The desired infrared (IR) wavelength range may refer to the wavelength range of IR light that can be detected by a suitable IR sensor (e.g., a complementary metal-oxide semiconductor (CMOS) or a charge-coupled device (CCD) sensor), such as between 830 nm and 860 nm or between 930 nm and 980 nm.

As also used herein, a substrate may refer to a medium within which an array of chirped gratings may be inscribed. A chirped grating may refer to a grating whose pitch and angle of orientation changes over the extent of the grating. The substrate may include one or more types of dielectric materials, such as glass, quartz, plastic, polymer, poly(methyl methacrylate) (PMMA), crystal, or ceramic. At least one type of material of the substrate may be transparent to visible light and NIR light. A thickness of the substrate may range from, for example, less than about 1 mm to less than about 10 mm. As used herein, a material may be “transparent” to a light beam if the light beam can pass through the material with a high transmission rate, such as larger than 60%, 75%, 80%, 90%, 95%, 98%, 99%, or higher, where a small portion of the light beam (e.g., less than 40%, 25%, 20%, 10%, 5%, 2%, 1%, or less) may be scattered, reflected, or absorbed by the material. The transmission rate (i.e., transmissivity) may be represented by either a photopically weighted or an unweighted average transmission rate over a range of wavelengths, or the lowest transmission rate over a range of wavelengths, such as the visible wavelength range.

An artificial reality system, such as a virtual reality (VR), augmented reality (AR), or mixed reality (MR) system, may include a near-eye display (e.g., a headset or a pair of glasses) configured to present content to a user via an electronic or optic display and, in some cases, may also include a console configured to generate content for presentation to the user and to provide the generated content to the near-eye display for presentation. To improve user interaction with presented content, the console may modify or generate content based on a location where the user is looking, which may be determined by tracking the user’s eye. Tracking the eye may include tracking the position and/or shape of the pupil of the eye, and/or the rotational position (gaze direction) of the eye. To track the eye, the near-eye display may illuminate a surface of the user’s eye using light sources mounted to or within the near-eye display, according to at least one embodiment. An imaging device (e.g., a camera) included in the vicinity of the near-eye display may then capture light reflected by various surfaces of the user’s eye. Light that is reflected specularly off the cornea of the user’s eye may result in “glints” in the captured image. One way to illuminate the eye to see the pupil as well as the glints is to use a two-dimensional (2D) array of light-emitting diodes (LEDs). According to embodiments of the invention, these LEDs may be placed within the user’s field of view. Techniques such as a centroiding algorithm may be used to accurately determine the locations of the glints on the eye in the captured image, and the rotational position (e.g., the gaze direction) of the eye may then be determined based on the locations of the glints relative to a known feature of the eye (e.g., the center of the pupil) within the captured image.

Positioning a single light source or a plurality of light sources within the user’s field of view may offer greater

eye-tracking accuracy than positioning the light sources at the periphery of the user's field of view. For example, the probability of capturing glints over all gaze angles of the eye is higher when the light sources are located within the user's field of view. Further, the light sources may be configured such that they are effectively invisible to the user. This may be accomplished by using light sources with a very small form factor, such as less than 500 μm , less than 400 μm , or less than 200 μm . The form factor may refer to a maximum dimension of the light source in a plane that is parallel to an emission surface of the light source. A form factor of 200 μm may be a lower limit of what an eye is able to resolve. Alternatively, a form factor of 200 μm may be an upper limit of what is bothersome to the user when the light source is within the user's field of view. For example, a light source with a form factor of 200 μm may appear similar to a dust speck on the user's glasses, and may not interfere with the user's vision through the glasses. Some examples of light sources with a very small form factor are vertical cavity surface emitting lasers (VCSELs) that have a bare die size of less than 160 μm and an emission cone with an angle of less than 25°, and micro-LEDs that have a bare die size of less than 200 μm and an emission cone with an angle of less than 30°. The die size may refer to a linear dimension of the VCSEL or the micro-LED in a plane that is parallel to an emission surface of the VCSEL or the micro-LED. For example, the VCSEL or the micro-LED may have a square shape within the plane that is parallel to the emission surface, such that each of the sides of the square has a linear dimension of less than 200 μm . Further, positioning the light sources within the user's field of view may offer greater flexibility in the placement and distribution of the light sources, such that the amount of light captured by the camera is maximized. Although the eye may be able to detect near infrared light from a light source that is very bright, the light sources may be operated at lower brightness levels to minimize this effect.

FIG. 1 is a simplified block diagram of an example artificial reality system environment 100 including a near-eye display 120, in accordance with certain embodiments. Artificial reality system environment 100 shown in FIG. 1 may include a near-eye display 120, an external imaging device 150, and an input/output interface 140 that are each coupled to a console 110. While FIG. 1 shows example artificial reality system environment 100 including one near-eye display 120, one external imaging device 150, and one input/output interface 140, any number of these components may be included in artificial reality system environment 100, or any of the components may be omitted. For example, there may be multiple near-eye displays 120 monitored by one or more external imaging devices 150 in communication with console 110. In alternative configurations, different or additional components may be included in artificial reality system environment 100.

Near-eye display 120 may be a head-mounted display that presents content to a user. Examples of content presented by near-eye display 120 include one or more of images, videos, audios, or some combination thereof. In some embodiments, audio may be presented via an external device (e.g., speakers and/or headphones) that receives audio information from near-eye display 120, console 110, or both, and presents audio data based on the audio information. Near-eye display 120 may include one or more rigid bodies, which may be rigidly or non-rigidly coupled to each other. A rigid coupling between rigid bodies may cause the coupled rigid bodies to act as a single rigid entity. A non-rigid coupling between rigid bodies may allow the rigid bodies to move relative to

each other. In various embodiments, near-eye display 120 may be implemented in any suitable form factor, including a pair of glasses. Some embodiments of near-eye display 120 are further described below with respect to FIGS. 2, 3, and 11. Additionally, in various embodiments, the functionality described herein may be used in a headset that combines images of an environment external to near-eye display 120 and content received from console 110, or from any other console generating and providing content to a user. Therefore, near-eye display 120, and methods for eye tracking described herein, may augment images of a physical, real-world environment external to near-eye display 120 with generated content (e.g., images, video, sound, etc.) to present an augmented reality to a user.

In various embodiments, near-eye display 120 may include one or more of display electronics 122, display optics 124, one or more locators 126, one or more position sensors 128, an eye-tracking unit 130, and an inertial measurement unit (IMU) 132. Near-eye display 120 may omit any of these elements or include additional elements in various embodiments. Additionally, in some embodiments, near-eye display 120 may include elements combining the function of various elements described in conjunction with FIG. 1.

Display electronics 122 may display images to the user according to data received from console 110. In various embodiments, display electronics 122 may include one or more display panels, such as a liquid crystal display (LCD), an organic light emitting diode (OLED) display, a micro-LED display, an active-matrix OLED display (AMOLED), a transparent OLED display (TOLED), or some other display. For example, in one implementation of near-eye display 120, display electronics 122 may include a front TOLED panel, a rear display panel, and an optical component (e.g., an attenuator, polarizer, or diffractive or spectral film) between the front and rear display panels. Display electronics 122 may include sub-pixels to emit light of a predominant color such as red, green, blue, white, or yellow. In some implementations, display electronics 122 may display a 3D image through stereo effects produced by two-dimensional panels to create a subjective perception of image depth. For example, display electronics 122 may include a left display and a right display positioned in front of a user's left eye and right eye, respectively. The left and right displays may present copies of an image shifted horizontally relative to each other to create a stereoscopic effect (i.e., a perception of image depth by a user viewing the image).

In certain embodiments, display optics 124 may display image content optically (e.g., using optical waveguides and couplers), or magnify image light received from display electronics 122, correct optical errors associated with the image light, and present the corrected image light to a user of near-eye display 120. In various embodiments, display optics 124 may include one or more optical elements. Example optical elements may include a substrate, optical waveguides, an aperture, a Fresnel lens, a convex lens, a concave lens, a filter, or any other suitable optical element that may affect image light emitted from display electronics 122. Display optics 124 may include a combination of different optical elements as well as mechanical couplings to maintain relative spacing and orientation of the optical elements in the combination. One or more optical elements in display optics 124 may have an optical coating, such as an anti-reflective coating, a reflective coating, a filtering coating, or a combination of different optical coatings.

Magnification of the image light by display optics **124** may allow display electronics **122** to be physically smaller, weigh less, and consume less power than larger displays. Additionally, magnification may increase a field of view of the displayed content. In some embodiments, display optics **124** may have an effective focal length larger than the spacing between display optics **124** and display electronics **122** to magnify image light projected by display electronics **122**. The amount of magnification of image light by display optics **124** may be adjusted by adding or removing optical elements from display optics **124**.

Display optics **124** may be designed to correct one or more types of optical errors, such as two-dimensional optical errors, three-dimensional optical errors, or a combination thereof. Two-dimensional errors may include optical aberrations that occur in two dimensions. Example types of two-dimensional errors may include barrel distortion, pin-cushion distortion, longitudinal chromatic aberration, and transverse chromatic aberration. Three-dimensional errors may include optical errors that occur in three dimensions. Example types of three-dimensional errors may include spherical aberration, comatic aberration, field curvature, and astigmatism. In some embodiments, content provided to display electronics **122** for display may be pre-distorted, and display optics **124** may correct the distortion when it receives image light from display electronics **122** generated based on the pre-distorted content.

Locators **126** may be objects located in specific positions on near-eye display **120** relative to one another and relative to a reference point on near-eye display **120**. Console **110** may identify locators **126** in images captured by external imaging device **150** to determine the artificial reality headset's position, orientation, or both. A locator **126** may be a light emitting diode (LED), a corner cube reflector, a reflective marker, a type of light source that contrasts with an environment in which near-eye display **120** operates, or some combinations thereof. In embodiments where locators **126** are active components (e.g., LEDs or other types of light emitting devices), locators **126** may emit light in the visible band (e.g., about 380 nm to 750 nm), in the infrared (IR) band (e.g., about 750 nm to 1 mm), in the ultraviolet band (e.g., about 10 nm to about 380 nm), in another portion of the electromagnetic spectrum, or in any combination of portions of the electromagnetic spectrum.

In some embodiments, locators **126** may be located beneath an outer surface of near-eye display **120**. A portion of near-eye display **120** between a locator **126** and an entity external to near-eye display **120** (e.g., external imaging device **150**, a user viewing the outer surface of near-eye display **120**) may be transparent to the wavelengths of light emitted or reflected by locators **126** or is thin enough to not substantially attenuate the light emitted or reflected by locators **126**. In some embodiments, the outer surface or other portions of near-eye display **120** may be opaque in the visible band, but is transparent in the IR band, and locators **126** may be under the outer surface and may emit light in the IR band.

External imaging device **150** may generate slow calibration data based on calibration parameters received from console **110**. Slow calibration data may include one or more images showing observed positions of locators **126** that are detectable by external imaging device **150**. External imaging device **150** may include one or more cameras, one or more video cameras, any other device capable of capturing images including one or more of locators **126**, or some combinations thereof. Additionally, external imaging device **150** may include one or more filters (e.g., to increase signal to noise

ratio). External imaging device **150** may be configured to detect light emitted or reflected from locators **126** in a field of view of external imaging device **150**. In embodiments where locators **126** include passive elements (e.g., retroreflectors), external imaging device **150** may include a light source that illuminates some or all of locators **126**, which may retro-reflect the light to the light source in external imaging device **150**. Slow calibration data may be communicated from external imaging device **150** to console **110**, and external imaging device **150** may receive one or more calibration parameters from console **110** to adjust one or more imaging parameters (e.g., focal length, focus, frame rate, sensor temperature, shutter speed, aperture, etc.).

Position sensors **128** may generate one or more measurement signals in response to motion of near-eye display **120**. Examples of position sensors **128** may include accelerometers, gyroscopes, magnetometers, other motion-detecting or error-correcting sensors, or some combinations thereof. For example, in some embodiments, position sensors **128** may include multiple accelerometers to measure translational motion (e.g., forward/back, up/down, or left/right) and multiple gyroscopes to measure rotational motion (e.g., pitch, yaw, or roll). In some embodiments, various position sensors may be oriented orthogonally to each other.

IMU **132** may be an electronic device that generates fast calibration data based on measurement signals received from one or more of position sensors **128**. Position sensors **128** may be located external to IMU **132**, internal to IMU **132**, or some combination thereof. Based on the one or more measurement signals from one or more position sensors **128**, IMU **132** may generate fast calibration data indicating an estimated position of near-eye display **120** relative to an initial position of near-eye display **120**. For example, IMU **132** may integrate measurement signals received from accelerometers over time to estimate a velocity vector and integrate the velocity vector over time to determine an estimated position of a reference point on near-eye display **120**. Alternatively, IMU **132** may provide the sampled measurement signals to console **110**, which may determine the fast calibration data. While the reference point may generally be defined as a point in space, in various embodiments, the reference point may also be defined as a point within near-eye display **120** (e.g., a center of IMU **132**).

Eye-tracking unit **130** may include one or more imaging devices configured to capture eye tracking data, which an eye-tracking module **118** in console **110** may use to track the user's eye. Eye tracking data may refer to data output by eye-tracking unit **130**. Example eye tracking data may include images captured by eye-tracking unit **130** or information derived from the images captured by eye-tracking unit **130**. Eye tracking may refer to determining an eye's position, including orientation and location of the eye, relative to near-eye display **120**. For example, eye-tracking module **118** may output the eye's pitch and yaw based on images of the eye captured by eye-tracking unit **130**. In various embodiments, eye-tracking unit **130** may measure electromagnetic energy reflected by the eye and communicate the measured electromagnetic energy to eye-tracking module **118**, which may then determine the eye's position based on the measured electromagnetic energy. For example, eye-tracking unit **130** may measure electromagnetic waves such as visible light, infrared light, radio waves, microwaves, waves in any other part of the electromagnetic spectrum, or a combination thereof reflected by an eye of a user.

Eye-tracking unit **130** may include one or more eye-tracking systems. An eye-tracking system may include an

imaging system to image one or more eyes and may optionally include a light emitter, which may generate light that is directed to an eye such that light reflected by the eye may be captured by the imaging system. For example, eye-tracking unit **130** may include a coherent light source (e.g., a VCSEL) emitting light in the visible spectrum or infrared spectrum, and a camera capturing the light reflected by the user's eye. As another example, eye-tracking unit **130** may capture reflected radio waves emitted by a miniature radar unit. Eye-tracking unit **130** may use low-power light emitters that emit light at frequencies and intensities that would not injure the eye or cause physical discomfort. Eye-tracking unit **130** may be arranged to increase contrast in images of an eye captured by eye-tracking unit **130** while reducing the overall power consumed by eye-tracking unit **130** (e.g., reducing power consumed by a light emitter and an imaging system included in eye-tracking unit **130**). For example, in some implementations, eye-tracking unit **130** may consume less than 100 milliwatts of power.

In some embodiments, eye-tracking unit **130** may include one light emitter and one camera to track each of the user's eyes. In other embodiments, eye-tracking unit **130** may include a plurality of light emitters and one camera to track each of the user's eyes. Eye-tracking unit **130** may also include different eye-tracking systems that operate together to provide improved eye tracking accuracy and responsiveness. For example, eye-tracking unit **130** may include a fast eye-tracking system with a fast response time and a slow eye-tracking system with a slower response time. The fast eye-tracking system may frequently measure an eye to capture data used by eye-tracking module **118** to determine the eye's position relative to a reference eye position. The slow eye-tracking system may independently measure the eye to capture data used by eye-tracking module **118** to determine the reference eye position without reference to a previously determined eye position. Data captured by the slow eye-tracking system may allow eye-tracking module **118** to determine the reference eye position with greater accuracy than the eye's position determined from data captured by the fast eye-tracking system. In various embodiments, the slow eye-tracking system may provide eye-tracking data to eye-tracking module **118** at a lower frequency than the fast eye-tracking system. For example, the slow eye-tracking system may operate less frequently or have a slower response time to conserve power.

Eye-tracking unit **130** may be configured to estimate the orientation of the user's eye. The orientation of the eye may correspond to the direction of the user's gaze within near-eye display **120**. The orientation of the user's eye may be defined as the direction of the foveal axis, which is the axis between the fovea (an area on the retina of the eye with the highest concentration of photoreceptors) and the center of the eye's pupil. In general, when a user's eyes are fixed on a point, the foveal axes of the user's eyes intersect that point. The pupillary axis of an eye may be defined as the axis that passes through the center of the pupil and is perpendicular to the corneal surface. In general, even though the pupillary axis and the foveal axis intersect at the center of the pupil, the pupillary axis may not directly align with the foveal axis. For example, the orientation of the foveal axis may be offset from the pupillary axis by approximately -1° to 8° laterally and about $\pm 4^\circ$ vertically. Because the foveal axis is defined according to the fovea, which is located in the back of the eye, the foveal axis may be difficult or impossible to measure directly in some eye tracking embodiments. Accordingly, in

some embodiments, the orientation of the pupillary axis may be detected and the foveal axis may be estimated based on the detected pupillary axis.

In general, the movement of an eye corresponds not only to an angular rotation of the eye, but also to a translation of the eye, a change in the torsion of the eye, and/or a change in the shape of the eye. Eye-tracking unit **130** may also be configured to detect the translation of the eye, which may be a change in the position of the eye relative to the eye socket. In some embodiments, the translation of the eye may not be detected directly, but may be approximated based on a mapping from a detected angular orientation. Translation of the eye corresponding to a change in the eye's position relative to the eye-tracking unit may also be detected. Translation of this type may occur, for example, due to a shift in the position of near-eye display **120** on a user's head. Eye-tracking unit **130** may also detect the torsion of the eye and the rotation of the eye about the pupillary axis. Eye-tracking unit **130** may use the detected torsion of the eye to estimate the orientation of the foveal axis from the pupillary axis. Eye-tracking unit **130** may also track a change in the shape of the eye, which may be approximated as a skew or scaling linear transform or a twisting distortion (e.g., due to torsional deformation). Eye-tracking unit **130** may estimate the foveal axis based on some combinations of the angular orientation of the pupillary axis, the translation of the eye, the torsion of the eye, and the current shape of the eye.

In some embodiments, eye-tracking unit **130** may include multiple emitters or at least one emitter that can project a structured light pattern on all portions or a portion of the eye. The structured light pattern may be distorted due to the shape of the eye when viewed from an offset angle. Eye-tracking unit **130** may also include at least one camera that may detect the distortions (if any) of the structured light pattern projected onto the eye. The camera may be oriented on a different axis to the eye than the emitter. By detecting the deformation of the structured light pattern on the surface of the eye, eye-tracking unit **130** may determine the shape of the portion of the eye being illuminated by the structured light pattern. Therefore, the captured distorted light pattern may be indicative of the 3D shape of the illuminated portion of the eye. The orientation of the eye may thus be derived from the 3D shape of the illuminated portion of the eye. Eye-tracking unit **130** can also estimate the pupillary axis, the translation of the eye, the torsion of the eye, and the current shape of the eye based on the image of the distorted structured light pattern captured by the camera.

Near-eye display **120** may use the orientation of the eye to, e.g., determine an inter-pupillary distance (IPD) of the user, determine gaze direction, introduce depth cues (e.g., blur image outside of the user's main line of sight), collect heuristics on the user interaction in the VR media (e.g., time spent on any particular subject, object, or frame as a function of exposed stimuli), some other functions that are based in part on the orientation of at least one of the user's eyes, or some combination thereof. Because the orientation may be determined for both eyes of the user, eye-tracking unit **130** may be able to determine where the user is looking. For example, determining a direction of a user's gaze may include determining a point of convergence based on the determined orientations of the user's left and right eyes. A point of convergence may be the point where the two foveal axes of the user's eyes intersect (or the nearest point between the two axes). The direction of the user's gaze may be the direction of a line passing through the point of convergence and the mid-point between the pupils of the user's eyes.

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Eye-tracking unit **130** is further described below with respect to, for example, FIGS. **3-9**.

Input/output interface **140** may be a device that allows a user to send action requests to console **110**. An action request may be a request to perform a particular action. For example, an action request may be to start or to end an application or to perform a particular action within the application. Input/output interface **140** may include one or more input devices. Example input devices may include a keyboard, a mouse, a game controller, a glove, a button, a touch screen, or any other suitable device for receiving action requests and communicating the received action requests to console **110**. An action request received by the input/output interface **140** may be communicated to console **110**, which may perform an action corresponding to the requested action. In some embodiments, input/output interface **140** may provide haptic feedback to the user in accordance with instructions received from console **110**. For example, input/output interface **140** may provide haptic feedback when an action request is received, or when console **110** has performed a requested action and communicates instructions to input/output interface **140**.

Console **110** may provide content to near-eye display **120** for presentation to the user in accordance with information received from one or more of external imaging device **150**, near-eye display **120**, and input/output interface **140**. In the example shown in FIG. **1**, console **110** may include an application store **112**, a headset tracking module **114**, a virtual reality engine **116**, and eye-tracking module **118**. Some embodiments of console **110** may include different or additional modules than those described in conjunction with FIG. **1**. Functions further described below may be distributed among components of console **110** in a different manner than is described here.

In some embodiments, console **110** may include a processor and a non-transitory computer-readable storage medium storing instructions executable by the processor. The processor may include multiple processing units executing instructions in parallel. The computer-readable storage medium may be any memory, such as a hard disk drive, a removable memory, or a solid-state drive (e.g., flash memory or dynamic random access memory (DRAM)). In various embodiments, the modules of console **110** described in conjunction with FIG. **1** may be encoded as instructions in the non-transitory computer-readable storage medium that, when executed by the processor, cause the processor to perform the functions further described below.

Application store **112** may store one or more applications for execution by console **110**. An application may include a group of instructions that, when executed by a processor, generates content for presentation to the user. Content generated by an application may be in response to inputs received from the user via movement of the user's eyes or inputs received from the input/output interface **140**. Examples of the applications may include gaming applications, conferencing applications, video playback application, or other suitable applications.

Headset tracking module **114** may track movements of near-eye display **120** using slow calibration information from external imaging device **150**. For example, headset tracking module **114** may determine positions of a reference point of near-eye display **120** using observed locators from the slow calibration information and a model of near-eye display **120**. Headset tracking module **114** may also determine positions of a reference point of near-eye display **120** using position information from the fast calibration information. Additionally, in some embodiments, headset track-

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ing module **114** may use portions of the fast calibration information, the slow calibration information, or some combination thereof, to predict a future location of near-eye display **120**. Headset tracking module **114** may provide the estimated or predicted future position of near-eye display **120** to VR engine **116**.

Headset tracking module **114** may calibrate the artificial reality system environment **100** using one or more calibration parameters, and may adjust one or more calibration parameters to reduce errors in determining the position of near-eye display **120**. For example, headset tracking module **114** may adjust the focus of external imaging device **150** to obtain a more accurate position for observed locators on near-eye display **120**. Moreover, calibration performed by headset tracking module **114** may also account for information received from IMU **132**. Additionally, if tracking of near-eye display **120** is lost (e.g., external imaging device **150** loses line of sight of at least a threshold number of locators **126**), headset tracking module **114** may re-calibrate some or all of the calibration parameters.

VR engine **116** may execute applications within artificial reality system environment **100** and receive position information of near-eye display **120**, acceleration information of near-eye display **120**, velocity information of near-eye display **120**, predicted future positions of near-eye display **120**, or some combination thereof from headset tracking module **114**. VR engine **116** may also receive estimated eye position and orientation information from eye-tracking module **118**. Based on the received information, VR engine **116** may determine content to provide to near-eye display **120** for presentation to the user. For example, if the received information indicates that the user has looked to the left, VR engine **116** may generate content for near-eye display **120** that mirrors the user's eye movement in a virtual environment. Additionally, VR engine **116** may perform an action within an application executing on console **110** in response to an action request received from input/output interface **140**, and provide feedback to the user indicating that the action has been performed. The feedback may be visual or audible feedback via near-eye display **120** or haptic feedback via input/output interface **140**.

Eye-tracking module **118** may receive eye-tracking data from eye-tracking unit **130** and determine the position of the user's eye based on the eye tracking data. The position of the eye may include an eye's orientation, location, or both relative to near-eye display **120** or any element thereof. Because the eye's axes of rotation change as a function of the eye's location in its socket, determining the eye's location in its socket may allow eye-tracking module **118** to more accurately determine the eye's orientation.

In some embodiments, eye-tracking unit **130** may output eye-tracking data including images of the eye, and eye-tracking module **118** may determine the eye's position based on the images. For example, eye-tracking module **118** may store a mapping between images captured by eye-tracking unit **130** and eye positions to determine a reference eye position from an image captured by eye-tracking unit **130**. Alternatively or additionally, eye-tracking module **118** may determine an updated eye position relative to a reference eye position by comparing an image from which the reference eye position is determined to an image from which the updated eye position is to be determined. Eye-tracking module **118** may determine eye position using measurements from different imaging devices or other sensors. For example, as described above, eye-tracking module **118** may use measurements from a slow eye-tracking system to determine a reference eye position, and then determine

updated positions relative to the reference eye position from a fast eye-tracking system until a next reference eye position is determined based on measurements from the slow eye-tracking system.

Eye-tracking module **118** may also determine eye calibration parameters to improve precision and accuracy of eye tracking. Eye calibration parameters may include parameters that may change whenever a user dons or adjusts near-eye display **120**. Example eye calibration parameters may include an estimated distance between a component of eye-tracking unit **130** and one or more parts of the eye, such as the eye's center, pupil, cornea boundary, or a point on the surface of the eye. Other example eye calibration parameters may be specific to a particular user and may include an estimated average eye radius, an average corneal radius, an average sclera radius, a map of features on the eye surface, and an estimated eye surface contour. In embodiments where light from the outside of near-eye display **120** may reach the eye (as in some augmented reality applications), the calibration parameters may include correction factors for intensity and color balance due to variations in light from the outside of near-eye display **120**. Eye-tracking module **118** may use eye calibration parameters to determine whether the measurements captured by eye-tracking unit **130** would allow eye-tracking module **118** to determine an accurate eye position (also referred to herein as "valid measurements"). Invalid measurements, from which eye-tracking module **118** may not be able to determine an accurate eye position, may be caused by the user blinking, adjusting the headset, or removing the headset, and/or may be caused by near-eye display **120** experiencing greater than a threshold change in illumination due to external light.

FIG. 2 is a perspective view of a simplified example near-eye display **200** including various sensors. Near-eye display **200** may be a specific implementation of near-eye display **120** of FIG. 1, and may be configured to operate as a virtual reality display, an augmented reality display, and/or a mixed reality display. Near-eye display **200** may include a frame **205** and a display **210**. Display **210** may be configured to present content to a user. In some embodiments, display **210** may include display electronics and/or display optics. For example, as described above with respect to near-eye display **120** of FIG. 1, display **210** may include an LCD display panel, an LED display panel, or an optical display panel (e.g., a waveguide display assembly).

Near-eye display **200** may further include various sensors **250a**, **250b**, **250c**, **250d**, and **250e** on or within frame **205**. In some embodiments, sensors **250a-250e** may include one or more depth sensors, motion sensors, position sensors, inertial sensors, or ambient light sensors. In some embodiments, sensors **250a-250e** may include one or more image sensors configured to generate image data representing different fields of views in different directions. In some embodiments, sensors **250a-250e** may be used as input devices to control or influence the displayed content of near-eye display **200**, and/or to provide an interactive VR/AR/MR experience to a user of near-eye display **200**. In some embodiments, sensors **250a-250e** may also be used for stereoscopic imaging.

In some embodiments, near-eye display **200** may further include one or more illuminators **230** to project light into the physical environment. The projected light may be associated with different frequency bands (e.g., visible light, infra-red light, ultra-violet light, etc.), and may serve various purposes. For example, illuminator(s) **230** may project light in a dark environment (or in an environment with low intensity of infra-red light, ultra-violet light, etc.) to assist sensors

250a-250e in capturing images of different objects within the dark environment. In some embodiments, illuminator(s) **230** may be used to project certain light pattern onto the objects within the environment. In some embodiments, illuminator(s) **230** may be used as locators, such as locators **126** described above with respect to FIG. 1.

In some embodiments, near-eye display **200** may also include a high-resolution camera **240**. Camera **240** may capture images of the physical environment in the field of view. The captured images may be processed, for example, by a virtual reality engine (e.g., virtual reality engine **116** of FIG. 1) to add virtual objects to the captured images or modify physical objects in the captured images, and the processed images may be displayed to the user by display **210** for AR or MR applications.

FIG. 3 is a perspective view of a simplified example near-eye display **300** including an example eye-tracking unit. FIG. 3 may be the perspective view of near-eye display **300** viewed from the side that faces the eyes of the user. As near-eye display **200**, near-eye display **300** may include a frame **305** and a display **310**. Frame **305** may be coupled to or embedded with one or more electrical or optical components. Display **310** may include display electronics and/or display optics, and may be configured to present content to a user. For example, as described above, display **310** may include an LCD display panel, an LED display panel, and/or an optical display panel (e.g., a waveguide display assembly).

Near-eye display **300** may include one or more light sources **320** and one or more cameras **330**. As discussed in further detail below, light source(s) **320** may be mounted on a substrate **340**, such that light source(s) **320** are positioned within the field of view of the eye of the user. Any suitable number of light source(s) **320** may be used, and light source(s) **320** may be arranged in any suitable pattern, such as a one-dimensional array or a two-dimensional array. Light source(s) **320** may be spaced closer together or farther apart than shown in FIG. 3. Substrate **340** may be mounted in front of the display **310**, or may be integrated with the display **310**. Substrate **340** may be transparent to visible light. Camera(s) **330** may be coupled to or embedded in frame **305**. Light source(s) **320** may emit light in certain frequency range (e.g., NIR) towards the eye of the user. The emitted light may be reflected by the eyes of the user. The reflected light may then be received by camera(s) **330** to form images that may indicate certain characteristics of light source(s) **320** and the eyes of the user. Based on the images captured by camera(s) **330**, an eye's position, including the orientation and location of the eye, may be determined. The gaze direction and/or gaze point of the user may also be determined based on the detected eye's position as described above with respect to FIG. 1. The image content displayed on display **310** may then be adjusted accordingly based on the gaze direction and/or gaze point of the user.

FIG. 4 is a cross-sectional view of an example near-eye display **400** including an example eye-tracking unit. It is noted that, even though FIG. 4 and other figures in the present disclosure show an eye of a user of a near-eye display for illustration purposes, the eye of the user is not a part of the corresponding near-eye display. Like near-eye displays **200** and **300**, near-eye display **400** may include a frame **405** and a display system that includes display electronics **410** and/or display optics **420** coupled to or embedded in frame **405**. As described above with respect to display electronics **122**, display electronics **410** may display images to the user according to data received from a console, such as console **110**. Display electronics **410** may include sub-

pixels to emit light of a predominant color, such as red, green, blue, white, or yellow. Display optics **420** may display image content optically (e.g., using optical waveguides and optical couplers), or magnify image light emitted by display electronics **410**, correct optical errors associated with the image light, and present the corrected image light to the user of near-eye display **400**. In various embodiments, display optics **420** may include one or more optical elements. Example optical elements may include a substrate, optical waveguides, optical couplers, an aperture, a Fresnel lens, a convex lens, a concave lens, a filter, or any other suitable optical element that may affect image light emitted from display electronics **410**. Display optics **420** may include a combination of different optical elements as well as mechanical couplings to maintain relative spacing and orientation of the optical elements in the combination. One or more optical elements in display optics **124** may have an optical coating, such as an anti-reflective coating, a reflective coating, a filtering coating, or a combination of different optical coatings.

Near-eye display **400** may include an eye-tracking unit that includes a light source **430** and a camera **440**. Light source **430** may be mounted on substrate **450**, which may be mounted on frame **450** in front of display optics **420**. Substrate **450** may be transparent to visible light. Camera **440** may be coupled to or embedded in frame **405**. Light source **430** may emit light towards an eye **490** of the user of near-eye display **400**, and may be positioned within a field of view of eye **490**. The emitted light may be reflected by the cornea **492** of eye **490** of the user. The reflected light may then be received by camera **440** to generate images that may indicate certain characteristics of light source **430** and eye **490** of the user. Based on the images captured by camera **440**, the position of eye **490**, including the orientation and location of eye **490**, may be determined. The gaze direction and/or gaze point of the user may be determined based on the detected position of eye **490** as described above with respect to FIG. 1. The image content displayed on the display system may then be adjusted accordingly based on the gaze direction and/or gaze point of the user.

In some implementations, light source **430** may include a coherent light source (i.e., a light source emitting light at a precise wavelength with negligible phase difference), such as a VCSEL. The VCSEL may illuminate a portion of the surface of eye **490**, such as cornea **492** or iris **494**, with coherent light. For example, the VCSEL may emit light in the infrared spectrum having a wavelength between about 830 nm and about 860 nm. As another example, the VCSEL may emit light having a wavelength between about 900 nm and about 1160 nm, such as between about 930 nm and about 980 nm. Alternatively, the VCSEL may emit light having a wavelength in the visible spectrum. However, illuminating the eye with light in the infrared spectrum may reduce interference and noise from visible light emitted by display electronics **410** or from external visible light that passes into near-eye display **400**, as in some augmented reality applications. The VCSEL may have a low power to prevent user discomfort or injury.

Although light source **430** may typically include a coherent light source, non-coherent light sources may be used in some implementations. For example, in some implementations, light source **430** may include an LED emitting light with wavelengths in the visible band or in the infrared band. For example, light source **430** may include a micro-LED. However, because LEDs emit light across a broader wavelength range than a laser, LEDs may produce images with lower contrast than those produced using a coherent light

source. In some embodiments, an additional light source that emits light at a different wavelength than the light source may be used to increase eye-tracking precision.

Camera **440** may capture light reflected by the portion of the eye surface illuminated by light source **430**. In one example, camera **440** may capture an image with a pixel array of 30 by 30 pixels, where a pixel may correspond to a resolution of about 15 to 40 μm of the eye surface. In this example, the imaged portion of the surface of eye **490** may have an area of between about 0.20 and about 1.44 square millimeters. In various embodiments, camera **440** may have increased resolution to increase eye tracking precision and accuracy. For example, camera **440** may have a quarter video graphic array (QVGA) resolution with a pixel array of 320 \times 240 pixels. Increasing the number of pixels included in camera **440** may allow the size of the surface of eye **490** corresponding to a pixel to be decreased, allow the area of the surface of eye **490** imaged by camera **440** to be increased, or both. However, using fewer pixels may beneficially reduce the power consumption of camera **440**, and illuminating and imaging a smaller area of the surface of the eye may beneficially reduce power consumption by light source **430**. In some embodiments, camera **440** may include an optical mouse sensor or other sensor capturing images at a very high frame rate. For example, in some cases, camera **440** may capture about 5,000 images per second to provide precise eye tracking data.

As shown in FIG. 4, the eye tracking unit may also include additional light sources, such as light sources **431** and **432**. Light sources **431** and **432** may be mounted on substrate **450**. Like light source **430**, light sources **431** and **432** may emit light towards eye **490**, and may be positioned within the field of view of eye **490**. The light emitted by light sources **431** and **432** may be reflected by cornea **492** of eye **490**. The reflected light may then be received by camera **440** and included in the images discussed above. For example, glints from each of light sources **430**, **431**, and **432** may be included in some or all of the images, and may be used to determine the gaze direction and/or gaze point of the user. Light sources **431** and **432** may have characteristics similar to those described above for light source **430**. For example, light sources **431** and **432** may include a VCSEL or a micro-LED. Although ray tracing is only shown in FIG. 4 for light source **430** for clarity of illustration, it should be understood that rays can also be traced to and from light sources **431** and **432**.

FIG. 5 illustrates light reflections and diffusions by an eye **550** during eye tracking using an eye-tracking unit **510**. Eye-tracking unit **510** may include a light source **512** and a camera **514** as described above with respect to FIG. 4. Although only one light source **512** is shown in FIG. 5, it should be understood that multiple additional light sources may be placed within the field of view of eye **550**. In other embodiments, eye-tracking unit **510** may include different and/or additional components than those depicted in FIG. 4. Light source **512** may include a VCSEL or a micro-LED and may emit light having a center axis that forms an angle **522** relative to a surface normal vector **520** of eye **550**. As discussed in further detail below, a beam diverting component may be positioned proximate to an emission area of light source **512** in order to achieve a desired light output direction. Surface normal vector **520** is orthogonal to a portion of the surface (e.g., cornea **552**) of eye **550** illuminated by light source **512**. In the example shown in FIG. 5, surface normal vector **520** may be the same as the foveal axis (a line from the center of pupil **556** to fovea **562**) of eye **550**. Alternatively, surface normal vector **520** may be

orthogonal to another portion of the surface of eye 550. Angle 522 may be measured between surface normal vector 520 and a line from a center of the portion of the surface of eye 550 illuminated by light source 512 to a center of the output aperture of light source 512. Angle 522 may be chosen to have any suitable value, such that at least a portion of the light from light source 512 is reflected by eye 550 and received by camera 514. For example, angle 522 may be chosen to be close to zero (e.g., between 5° and 10°) in order to minimize any distortions caused by larger incident angles, but greater than zero to prevent the light from being reflected directly back at light source 512 by eye 550. Although not shown, various reflectors and/or other optical components may be used to direct light reflected by eye 550 toward camera 514. For example, a plurality of reflectors (e.g., dichroic mirrors such as hot mirrors) may be immersed in a transparent substrate that may be positioned within the field of view of eye 550. Each reflector may reflect light in a first band of the optical spectrum (e.g., IR light or NIR light) and transmit light in a second band of the optical spectrum (e.g., visible light).

Camera 514 may be mounted at a camera angle 524 relative to surface normal vector 520 of eye 550. Camera 514 may be mounted outside of the field of view of eye 550, such that camera 514 does not interfere with the user's perception of the scene. Camera angle 524 may be measured between surface normal vector 520 and a line from a center of the portion of the surface of eye 550 illuminated by light source 512 to a center of the image sensor or light input aperture of camera 514. In some embodiments, a difference between angle 522 and camera angle 524 may be less than a threshold amount so that camera 514 may capture images via specular reflections of light incident on cornea 552 of eye 550, which may beneficially increase contrast of the resulting image and minimize light power loss and power consumption.

The light emitted by light source 512 may substantially uniformly illuminate a portion of the eye surface (e.g., cornea 552). A portion of the emitted light may be reflected specularly by cornea 552 of eye 550 and captured by camera 514. In some cases, the light incident on eye 550 may propagate into the eye for a small distance before being reflected. At least some portions of the light may enter eye 550 through cornea 552 and reach iris 554, pupil 556, lens 558, or retina 560 of eye 550. Because the eye surface and the interfaces within eye 550 (e.g., surface of iris 554 or pupil 556) may be rough (e.g., due to features such as capillaries or bumps), the eye surface and the interfaces within eye 550 may scatter the incident light in multiple directions. Different portions of the eye surface and the interfaces within eye 550 may have different arrangements of features. Thus, an intensity pattern of the light reflected by eye 550 may depend on the arrangement of features within the illuminated portion of eye 550, which may allow identification of the portion of the eye from the intensity pattern.

Camera 514 may collect and project light reflected by the illuminated portion of eye 550 onto an image sensor of camera 514. Camera 514 may also correct one or more optical errors (such as those described with respect to the display optics 124) to improve the contrast and other properties of the images captured by the image sensor of camera 514. In some embodiments, camera 514 may also magnify the reflected light. In some embodiments, camera 514 may enlarge the images. The image sensor of camera 514 may capture incident light focused by a lens assembly of camera 514. Thus, camera 514 may effectively capture an image of light source 512 (the emitted light of which is reflected

specularly by the cornea of the eye) reflected by the eye, resulting in a "glint" in the captured image. Because of the scattering (diffusive reflections) at the eye surface and internal interfaces of the eye, light incident on a point of the image sensor may include light reflected from multiple points within the illuminated portion of eye 550, and thus may be the result of the interference of the light reflected from the multiple points. Thus, the image sensor of camera 514 may also capture a diffraction or speckle pattern formed by a combination of light reflected from multiple points of the surface of eye 550.

Each pixel of the image sensor may include a light-sensitive circuit that can output a current or voltage signal proportional to the intensity of the light incident on the pixel. In some embodiments, the pixels of the image sensor may be sensitive to light in a narrow wavelength band. In some other embodiments, the pixels of the image sensor may have a wide-band or multi-band sensitivity. For example, the image sensor of camera 514 may include a complementary metal-oxide semiconductor (CMOS) pixel array, which may be used with light having a wavelength less than about 850 nm. As another example, the image sensor of camera 514 may include an indium gallium arsenide (InGaAs) alloy pixel array. Such an image sensor may be used with light having a wavelength between about 900 nm and about 1160 nm.

In some embodiments, to determine a position change of eye 550, an eye-tracking module (e.g., eye-tracking module 118 of FIG. 1) may determine a pixel shift between images. Multiplying the pixel shift by a calibrated distance per pixel may allow the eye-tracking module to determine a distance the surface (e.g., cornea 552) of eye 550 has shifted. For example, if the glint captured in one image is shifted by two pixels relative to the glint captured in a previous image, and each pixel corresponds to a distance of 10 μm at the surface of eye 550, the surface of eye 550 may have moved about 20 μm.

Alternatively or additionally, the eye-tracking module may determine the position of the eye in a captured image by comparing the captured images with one or more previous images having known positions of the eye. For example, the eye-tracking module may include a database of images that are each associated with a reference eye position. By matching the captured image with a stored image, the eye-tracking module may determine that the eye is at the reference eye position associated with the stored image. In some embodiments, the eye-tracking module may identify a feature in a portion of a captured image. The feature may include a diffraction or optical flow pattern associated with a particular portion of eye 550. For example, the eye-tracking module may determine the eye position by retrieving a reference eye position associated with the feature (which was also captured in a reference image), determining a pixel shift between the feature in the captured image and the feature in the reference image, and determining the eye position by modifying the reference eye position according to the determined pixel shift using the calibrated distance per pixel as described above.

As discussed above, camera 514 may effectively capture an image of light source 512 reflected by cornea 552 of eye 550. In some cases, the light source may be an extended source rather than a point source. Thus, the captured image (i.e., glint) of light source 512 may have a shape of a circle, a rectangle, an oval, or an irregular shape, and the spatial structure of light source 512 may be captured in the image. The extended shape of the glint and/or the spatial structure captured in the image of the light source may cause errors when determining the relative location of the glint in the

image using, for example, the centroiding algorithm. The errors may affect the accuracy of eye tracking when the relative location (e.g., pixel shift) of the glint in the image is used to determine the corneal location in 3D space. Therefore, the light source **512** may have an emission area with a small form factor that is much less than 200 μm . The small emission area of a VCSEL or a micro-LED would appear more like a point source than an extended source in the image and reduce the size of the resulting glint on the captured image. A VCSEL or a micro-LED that has a bare die size less than 200 μm would have an emission area with a linear dimension that is significantly smaller than 200 μm because the emission area of the VCSEL or micro-LED is much smaller than the bare die size in order to accommodate other components, such as the bond part. For example, a diameter of the emission area may be less than 20 μm . A smaller glint size in the captured image may lead to a more precise glint location determination and more accurate eye tracking.

According to certain aspects of the present disclosure, a light source or a plurality of light sources may be mounted on a transparent substrate that can be positioned in front of the user, such that the light source or plurality of light sources are within the user's field of view. The light source or plurality of light sources may be used for illumination and imaging in eye tracking. A beam diverting component may be provided for each light source, in order to direct light from the light source toward the eye of the user. The beam diverting component may cause at least a portion of the light from the light source to be incident on the eye of the user at an angle with respect to a vector that is normal to a surface of the eye of the user.

Because visible light is allowed to pass through the substrate, the substrate can be positioned in front of the user's eyes without obstructing the user's field of view. For example, in an AR application, the user can look through the substrate to see the outside world. In a VR application, the user can look through the substrate to view the displayed content. At the same time, light from a light source for eye illumination may be directed to the user's eye (e.g., cornea), and may then be reflected by the eye to a camera to form the glints in images captured by the camera for eye tracking.

FIG. 6 is a simplified diagram illustrating an example illuminator **600** for eye tracking in an example near-eye display, according to certain embodiments. FIG. 6 is merely illustrative and is not drawn to scale. Illuminator **600** may include a substrate **605** that positioned in front of (e.g., at a distance of about 10-20 mm from) a user's eye **640** and within the field of view of user's eye **640**. Substrate **605** may include one or more types of dielectric materials, such as glass, quartz, plastic, polymer, PMMA, crystal, or ceramic, and may be transparent to, for example, both visible light and NIR light. In some implementations, substrate **605** may be a part of glasses of the near-eye display or a part of display optics described above. Substrate **605** may have a thickness less than about 10 mm, and may have any suitable shape, such as cuboidal, or may have a curved surface. For example, a surface **670** of substrate **605** may be flat or curved. Further, some or all of substrate **605** may be coated with a conductive material that may or may not be transparent to visible light. The conductive material may include any suitable conductor, such as graphene or a transparent conductive oxide.

As shown in FIG. 6, a plurality of light sources **610** may be mounted on substrate **605**. For example, light sources **610** may be LEDs, micro-LEDs, inorganic LEDs, OLEDs, or VCSELs. Light sources **610** may be attached to substrate

605 in any suitable manner, such as bonding, gluing, or soldering. For example, light sources **610** may be die-bonded to substrate **605** using metal-loaded conductive adhesives. Further, light sources **610** may be wire-bonded to the conductive coating on surface **670** of substrate **605** via wire **660**. In addition, electrodes of light sources **610** may be electrically connected to a conductive circuit trace **650** within substrate **605**. Conductive circuit trace **650** may be used to control the activity of light sources **610**. Although a plurality of light sources **610** are shown in FIG. 6, other embodiments of the illuminator **600** may have a single light source **610**. Further, the plurality of light sources **610** may be arranged in a one-dimensional line or a two-dimensional array.

Each light source **610** emits light having an emission cone **620** whose axis is normal to a top surface of the light source **610**. For example, each light source **610** may be a VCSEL having an emission cone **620** with an angle **680** of less than 25° or a micro-LED having an emission cone **620** with an angle **680** of less than 30° . Light sources **610** may be surrounded by or immersed in an encapsulation layer **630** that is an index matched layer, such that a refractive index of encapsulation layer **630** matches a refractive index of substrate **605**. Encapsulation layer **630** may protect light sources **610** from damage.

As shown in FIG. 6, an axis **615** of each emission cone **620** is normal to the top surface of light source **610** and substrate **605**. As a result, light from some light sources **610** may not be angled directly toward eye **640**. This may cause some or all of the light from light sources **610** to be wasted by not reaching eye **640**. This may be especially problematic for light sources **610** that are positioned near the outer edges of substrate **605**, due to the narrow angle **680** of emission cone **620**. Some embodiments may address this issue by making surface **670** of substrate **605** curved. However, it may be difficult to bond light sources **610** on a curved surface.

FIG. 7 is a simplified diagram illustrating an example illuminator **700** for eye tracking in an example near-eye display, according to certain embodiments. FIG. 7 is merely illustrative and is not drawn to scale. The elements shown in FIG. 7 are similar to those shown in FIG. 6, except that each light source **710** is provided with a beam diverting component (not shown in FIG. 7) that directs light from the light source **710** toward eye **740**. The beam diverting components for light sources **710** near the outer edges of substrate **705** may be configured to bend the light at a larger angle, in order to direct the light toward eye **740**. Alternatively, some or all of the beam diverting components may bend the light at the same angle, such as an array of light sources that are arranged in a circle whose center is aligned with a center of eye **740**. The beam diverting components are further described below with respect to FIGS. 8A-8E.

The distribution of the light emitted from light sources **710** and directed by the beam diverting components toward eye **740** may be controlled by the beam diverting components. For example, each beam diverting component may direct the light from a respective light source **710** in a different direction and may illuminate a different area on eye **740**, depending on the location of light source **710** and the angle at which the beam diverting component bends the light. For example, as discussed above, the beam diverting components for light sources **710** near the outer edges of substrate **705** may be configured to bend the light at a larger angle, while the beam diverting components for light sources **710** near the middle of substrate **705** (i.e., closest to a normal vector of eye **740**) may be configured to bend the

light at a smaller angle. Because each light source **710** may have a narrow emission cone, the beam diverting components may prevent some or all of the light from missing the target location. Further, each area of eye **740** may be illuminated approximately uniformly by light sources **710**. Using multiple light sources **710** may allow multiple glints to be generated, which may improve eye-tracking accuracy.

FIGS. **8A-8E** are simplified diagrams illustrating example illuminators for eye tracking having various beam diverting components, according to certain embodiments. FIGS. **8A-8E** are merely illustrative and are not drawn to scale. As shown in FIGS. **8A-8E**, a light source **810** having an emission area **815** is mounted on a substrate **805**. Beam diverting components **880**, **885**, **890**, **895**, and **898** may change the direction of light from emission area **815**. For example, light source **810** may be configured such that emission area **815** emits light normal to substrate **805**. However, beam diverting components may change the direction of the light, such that the light is directed toward an eye of the user. For example, beam diverting components **880**, **885**, **890**, **895**, and **898** may bend the light such that at least a portion of the light is incident on the eye at an angle with respect to a vector that is normal to a surface of the eye. As discussed above, the angle may be selected such that at least some of the light is reflected by the eye and is incident on the camera. Alternatively, beam diverting components **880**, **885**, **890**, **895**, and **898** may bend the light such that more of the light is incident on the surface of the eye.

FIG. **8A** illustrates an example illuminator for eye tracking having beam diverting component **880** that is a micro-prism, according to certain embodiments. A shape and a position of the micro-prism may be adjusted to customize the angle at which the light from emission area **815** is bent. The micro-prism may be incorporated into the illuminator and aligned with light source **810** by any suitable method. For example, the micro-prism or an array of micro-prisms may be molded from a substrate, and then the micro-prism may be placed on light source **810** and aligned with emission area **815**. Further, the micro-prism may be patterned into a substrate by grayscale lithography or photolithography. The micro-prism may also be deposited on light source **810** by pick-and-place deposition.

FIG. **8B** illustrates an example illuminator for eye tracking having beam diverting component **885** that is an off-axis micro-lens, according to certain embodiments. A shape and a position of the micro-lens may be adjusted to customize the angle at which the light from emission area **815** is bent. The micro-lens may be incorporated into the illuminator and aligned with light source **810** by any suitable method. For example, the micro-lens or an array of micro-lenses may be molded from a substrate, and then the micro-lens may be placed on light source **810** such that an optical axis of the micro-lens is offset from an optical axis of emission area **815**. In addition, the micro-lens may be formed by three-dimensional (3D) direct write lithography, injection molding, or inkjet printing. A flat metalens may be formed by nanoimprinting or optical lithography. Further, the micro-lens may be deposited on light source **810** by inkjet printing. The micro-lens may also be deposited on light source **810** by pick-and-place deposition.

FIG. **8C** illustrates an example illuminator for eye tracking having beam diverting component **890** that is an inverse micro-prism, according to certain embodiments. A shape and a position of the inverse micro-prism may be adjusted to customize the angle at which the light from emission area **815** is bent. The inverse micro-prism may be incorporated into the illuminator and aligned with light source **810** by any

suitable method. For example, the inverse micro-prism may be patterned into a substrate by grayscale lithography or photolithography, and may then be placed on light source **810** and aligned with emission area **815**. Further, the inverse micro-prism may be formed by injection molding. In addition, the inverse micro-prism may be formed by diamond turning in an encapsulation layer that surrounds light source **810**. The inverse micro-prism may also be deposited on light source **810** by pick-and-place deposition. For the illuminators shown in FIGS. **8A**, **8B**, and **8C**, the light sources **810** and beam diverting components **880**, **885**, and **890** may be immersed in an encapsulant (not shown), where the encapsulant may have a different refractive index than the beam diverting components **880**, **885**, and **890**.

FIGS. **8D** and **8E** illustrate example illuminators for eye tracking having beam diverting components **895** and **897**, respectively, that are gratings, according to certain embodiments. A period, slant angle, material(s), shape, and/or position of the grating may be adjusted to customize the angle at which the light from emission area **815** is bent. For example, a shorter grating period diffracts light at a larger angle and may be used on the outer edges of the grating. Slanted gratings increase the amount of light diffracted in the -1 or $+1$ diffraction order. The grating may be incorporated into the illuminator and aligned with light source **810** by any suitable method. For example, the grating may be formed in a substrate by etching and nanoimprinting, or by holography. Further, as shown in FIG. **8D**, the grating may be a surface relief grating (SRG) **896** that is formed by direct imprinting on a surface of light source **810**. In addition, the grating may be fabricated as a roll that forms an encapsulation layer on light source **810**. The grating may also be a thin phase hologram of a thick volume Bragg grating **897**, as shown in FIG. **8E**.

FIG. **8F** illustrates an example illuminator for eye tracking having beam diverting component **898** that is an inclined plane, according to certain embodiments. A shape and a position of the inclined plane may be adjusted to customize the angle at which the light from emission area **815** is bent. The inclined plane may be incorporated into the illuminator and aligned with light source **810** by any suitable method. For example, grayscale lithography may be used to pattern small bumps on a bottom surface of light source **810**, such that a coefficient of friction is sufficient to prevent light source **810** from sliding off of the inclined plane. Alternatively, light source **810** may be mounted with solder bumps, where the bonding pads have different thicknesses, different amounts of solder is used, and/or light source **810** is held at a predetermined angle that is not parallel with the bonded surface of substrate **805**.

FIG. **9** is a flow chart **900** illustrating an example method of eye illumination for eye tracking in a near-eye display, according to certain embodiments. The method may be performed by, for example, eye-tracking unit **130** in near-eye display **120** of FIG. **1** and eye-tracking unit **510** of FIG. **5**.

At block **910**, a light source (e.g., a VCSEL or a micro-LED) of an eye-tracking unit in a near-eye display device may emit light. The light source may be within a field of view of an eye of a user. In order to prevent the user from perceiving or being affected by the presence of the light source, a maximum dimension of the light source in a plane parallel to an emission surface of the light source may be less than $200\ \mu\text{m}$. The light may be in the NIR region of the spectrum, such as between $830\ \text{nm}$ and $860\ \text{nm}$, or between $930\ \text{nm}$ and $980\ \text{nm}$. An angle of an emission cone of the light from the light source may be less than 30° .

At block **920**, a beam diverting component may change the direction of the light from the light source in order to direct the light from the light source toward the eye of the user. For example, as discussed above, the beam diverting component, such as the beam diverting components **880**, **885**, **890**, **896**, **897**, and **898** shown in FIGS. **8A**, **8B**, **8C**, **8D**, **8E**, and **8F**, respectively, may be designed such that at least a portion of the light is incident on the eye of the user at an angle with respect to a vector that is normal to a surface of the eye of the user. Other portions of the light may be incident on the eye of the user at other angles, or may not be incident on the eye of the user.

At block **930**, a camera of the eye-tracking unit may receive light that is reflected by the eye of the user. The light reflected by the eye of the user may include light specularly reflected by the cornea of the eye and light diffusively reflected or diffracted by features within the eye, such as features on the iris or pupil of the eye.

At block **940**, the camera may generate an image frame including an image of the light source (a “glint”) reflected by the eye of the user, by detecting the light reflected from the eye of the user using an image sensor. In embodiments where multiple light sources are used, multiple glints may be captured in the captured image frame. The location(s) of the glint(s) in the captured image frame and/or other features in the captured image frame that correspond to features in different areas of the eye may then be used to determine a position of the user’s eye as described above.

Embodiments of the invention may include or be implemented in conjunction with an artificial reality system. Artificial reality is a form of reality that has been adjusted in some manner before presentation to a user, which may include, e.g., a virtual reality (VR), an augmented reality (AR), a mixed reality (MR), a hybrid reality, or some combination and/or derivatives thereof. Artificial reality content may include completely generated content or generated content combined with captured (e.g., real-world) content. The artificial reality content may include video, audio, haptic feedback, or some combination thereof, and any of which may be presented in a single channel or in multiple channels (such as stereo video that produces a three-dimensional effect to the viewer). Additionally, in some embodiments, artificial reality may also be associated with applications, products, accessories, services, or some combination thereof, that are used to, e.g., create content in an artificial reality and/or are otherwise used in (e.g., perform activities in) an artificial reality. The artificial reality system that provides the artificial reality content may be implemented on various platforms, including a head-mounted display (HMD) connected to a host computer system, a standalone HMD, a mobile device or computing system, or any other hardware platform capable of providing artificial reality content to one or more viewers.

FIG. **10** is a perspective view of an example near-eye display in the form of a head-mounted display (HMD) device **1000** for implementing some of the example near-eye displays (e.g., near-eye display **120**) disclosed herein. HMD device **1000** may be a part of, e.g., a virtual reality (VR) system, an augmented reality (AR) system, a mixed reality (MR) system, or some combinations thereof. HMD device **1000** may include a body **1020** and a head strap **1030**. FIG. **10** shows a top side **1023**, a front side **1025**, and a right side **1027** of body **1020** in the perspective view. Head strap **1030** may have an adjustable or extendible length. There may be a sufficient space between body **1020** and head strap **1030** of HMD device **1000** for allowing a user to mount HMD device **1000** onto the user’s head. In various embodiments, HMD

device **1000** may include additional, fewer, or different components. For example, in some embodiments, HMD device **1000** may include eyeglass temples and temples tips as shown in, for example, FIGS. **2-4**, rather than head strap **1030**.

HMD device **1000** may present to a user media including virtual and/or augmented views of a physical, real-world environment with computer-generated elements. Examples of the media presented by HMD device **1000** may include images (e.g., two-dimensional (2D) or three-dimensional (3D) images), videos (e.g., 2D or 3D videos), audios, or some combinations thereof. The images and videos may be presented to each eye of the user by one or more display assemblies (not shown in FIG. **10**) enclosed in body **1020** of HMD device **1000**. In various embodiments, the one or more display assemblies may include a single electronic display panel or multiple electronic display panels (e.g., one display panel for each eye of the user). Examples of the electronic display panel(s) may include, for example, a liquid crystal display (LCD), an organic light emitting diode (OLED) display, an inorganic light emitting diode (ILED) display, a micro-LED display, an active-matrix organic light emitting diode (AMOLED) display, a transparent organic light emitting diode (TOLED) display, some other display, or some combinations thereof. HMD device **1000** may include two eye box regions.

In some implementations, HMD device **1000** may include various sensors (not shown), such as depth sensors, motion sensors, position sensors, and eye tracking sensors. Some of these sensors may use a structured light pattern for sensing. In some implementations, HMD device **1000** may include an input/output interface for communicating with a console. In some implementations, HMD device **1000** may include a virtual reality engine (not shown) that can execute applications within HMD device **1000** and receive depth information, position information, acceleration information, velocity information, predicted future positions, or some combination thereof of HMD device **1000** from the various sensors. In some implementations, the information received by the virtual reality engine may be used for producing a signal (e.g., display instructions) to the one or more display assemblies. In some implementations, HMD device **1000** may include locators (not shown, such as locators **126**) located in fixed positions on body **1020** relative to one another and relative to a reference point. Each of the locators may emit light that is detectable by an external imaging device.

FIG. **11** is a simplified block diagram of an example electronic system **1100** of an example near-eye display (e.g., HMD device) for implementing some of the examples disclosed herein. Electronic system **1100** may be used as the electronic system of HMD device **1000** or other near-eye displays described above. In this example, electronic system **1100** may include one or more processor(s) **1110** and a memory **1120**. Processor(s) **1110** may be configured to execute instructions for performing operations at a number of components, and can be, for example, a general-purpose processor or microprocessor suitable for implementation within a portable electronic device. Processor(s) **1110** may be communicatively coupled with a plurality of components within electronic system **1100**. To realize this communicative coupling, processor(s) **1110** may communicate with the other illustrated components across a bus **1140**. Bus **1140** may be any subsystem adapted to transfer data within electronic system **1100**. Bus **1140** may include a plurality of computer buses and additional circuitry to transfer data.

Memory **1120** may be coupled to processor(s) **1110**. In some embodiments, memory **1120** may offer both short-term and long-term storage and may be divided into several units. Memory **1120** may be volatile, such as static random access memory (SRAM) and/or dynamic random access memory (DRAM) and/or non-volatile, such as read-only memory (ROM), flash memory, and the like. Furthermore, memory **1120** may include removable storage devices, such as secure digital (SD) cards. Memory **1120** may provide storage of computer-readable instructions, data structures, program modules, and other data for electronic system **1100**. In some embodiments, memory **1120** may be distributed into different hardware modules. A set of instructions and/or code might be stored on memory **1120**. The instructions might take the form of executable code that may be executable by electronic system **1100**, and/or might take the form of source and/or installable code, which, upon compilation and/or installation on electronic system **1100** (e.g., using any of a variety of generally available compilers, installation programs, compression/decompression utilities, etc.), may take the form of executable code.

In some embodiments, memory **1120** may store a plurality of application modules **1122** through **1124**, which may include any number of applications. Examples of applications may include gaming applications, conferencing applications, video playback applications, or other suitable applications. The applications may include a depth sensing function or eye tracking function. Application modules **1122-1124** may include particular instructions to be executed by processor(s) **1110**. In some embodiments, certain applications or parts of application modules **1122-1124** may be executable by other hardware modules **1180**. In certain embodiments, memory **1120** may additionally include secure memory, which may include additional security controls to prevent copying or other unauthorized access to secure information.

In some embodiments, memory **1120** may include an operating system **1125** loaded therein. Operating system **1125** may be operable to initiate the execution of the instructions provided by application modules **1122-1124** and/or manage other hardware modules **1180** as well as interfaces with a wireless communication subsystem **1130** which may include one or more wireless transceivers. Operating system **1125** may be adapted to perform other operations across the components of electronic system **1100** including threading, resource management, data storage control and other similar functionality.

Wireless communication subsystem **1130** may include, for example, an infrared communication device, a wireless communication device and/or chipset (such as a Bluetooth® device, an IEEE 802.11 device, a Wi-Fi device, a WiMax device, cellular communication facilities, etc.), and/or similar communication interfaces. Electronic system **1100** may include one or more antennas **1134** for wireless communication as part of wireless communication subsystem **1130** or as a separate component coupled to any portion of the system. Depending on desired functionality, wireless communication subsystem **1130** may include separate transceivers to communicate with base transceiver stations and other wireless devices and access points, which may include communicating with different data networks and/or network types, such as wireless wide-area networks (WWANs), wireless local area networks (WLANs), or wireless personal area networks (WPANs). A WWAN may be, for example, a WiMax (IEEE 802.16) network. A WLAN may be, for example, an IEEE 802.11x network. A WPAN may be, for example, a Bluetooth network, an IEEE 802.15x, or some

other types of network. The techniques described herein may also be used for any combination of WWAN, WLAN, and/or WPAN. Wireless communications subsystem **1130** may permit data to be exchanged with a network, other computer systems, and/or any other devices described herein. Wireless communication subsystem **1130** may include a means for transmitting or receiving data, such as identifiers of HMD devices, position data, a geographic map, a heat map, photos, or videos, using antenna(s) **1134** and wireless link(s) **1132**. Wireless communication subsystem **1130**, processor(s) **1110**, and memory **1120** may together comprise at least a part of one or more of a means for performing some functions disclosed herein.

Embodiments of electronic system **1100** may also include one or more sensors **1190**. Sensor(s) **1190** may include, for example, an image sensor, an accelerometer, a pressure sensor, a temperature sensor, a proximity sensor, a magnetometer, a gyroscope, an inertial sensor (e.g., a module that combines an accelerometer and a gyroscope), an ambient light sensor, or any other similar module operable to provide sensory output and/or receive sensory input, such as a depth sensor or a position sensor. For example, in some implementations, sensor(s) **1190** may include one or more inertial measurement units (IMUs) and/or one or more position sensors. An IMU may generate calibration data indicating an estimated position of the HMD device relative to an initial position of the HMD device, based on measurement signals received from one or more of the position sensors. A position sensor may generate one or more measurement signals in response to motion of the HMD device. Examples of the position sensors may include, but are not limited to, one or more accelerometers, one or more gyroscopes, one or more magnetometers, another suitable type of sensor that detects motion, a type of sensor used for error correction of the IMU, or some combination thereof. The position sensors may be located external to the IMU, internal to the IMU, or some combination thereof. At least some sensors may use a structured light pattern for sensing.

Electronic system **1100** may include a display module **1160**. Display module **1160** may be a near-eye display, and may graphically present information, such as images, videos, and various instructions, from electronic system **1100** to a user. Such information may be derived from one or more application modules **1122-1124**, virtual reality engine **1126**, one or more other hardware modules **1180**, a combination thereof, or any other suitable means for resolving graphical content for the user (e.g., by operating system **1125**). Display module **1160** may use liquid crystal display (LCD) technology, light-emitting diode (LED) technology (including, for example, OLED, ILED, mLED, AMOLED, TOLED, etc.), light emitting polymer display (LPD) technology, or some other display technology.

Electronic system **1100** may include a user input/output module **1170**. User input/output module **1170** may allow a user to send action requests to electronic system **1100**. An action request may be a request to perform a particular action. For example, an action request may be to start or end an application or to perform a particular action within the application. User input/output module **1170** may include one or more input devices. Example input devices may include a touchscreen, a touch pad, microphone(s), button(s), dial(s), switch(es), a keyboard, a mouse, a game controller, or any other suitable device for receiving action requests and communicating the received action requests to electronic system **1100**. In some embodiments, user input/output module **1170** may provide haptic feedback to the user in accordance with instructions received from electronic system

1100. For example, the haptic feedback may be provided when an action request is received or has been performed.

Electronic system 1100 may include a camera 1150 that may be used to take photos or videos of a user, for example, for tracking the user's eye position. Camera 1150 may also be used to take photos or videos of the environment, for example, for VR, AR, or MR applications. Camera 1150 may include, for example, a complementary metal-oxide-semiconductor (CMOS) image sensor with a few millions or tens of millions of pixels. In some implementations, camera 1150 may include two or more cameras that may be used to capture 3-D images.

In some embodiments, electronic system 1100 may include a plurality of other hardware modules 1180. Each of other hardware modules 1180 may be a physical module within electronic system 1100. While each of other hardware modules 1180 may be permanently configured as a structure, some of other hardware modules 1180 may be temporarily configured to perform specific functions or temporarily activated. Examples of other hardware modules 1180 may include, for example, an audio output and/or input module (e.g., a microphone or speaker), a near field communication (NFC) module, a rechargeable battery, a battery management system, a wired/wireless battery charging system, etc. In some embodiments, one or more functions of other hardware modules 1180 may be implemented in software.

In some embodiments, memory 1120 of electronic system 1100 may also store a virtual reality engine 1126. Virtual reality engine 1126 may execute applications within electronic system 1100 and receive position information, acceleration information, velocity information, predicted future positions, or some combination thereof of the HMD device from the various sensors. In some embodiments, the information received by virtual reality engine 1126 may be used for producing a signal (e.g., display instructions) to display module 1160. For example, if the received information indicates that the user has looked to the left, virtual reality engine 1126 may generate content for the HMD device that mirrors the user's movement in a virtual environment. Additionally, virtual reality engine 1126 may perform an action within an application in response to an action request received from user input/output module 1170 and provide feedback to the user. The provided feedback may be visual, audible, or haptic feedback. In some implementations, processor(s) 1110 may include one or more GPUs that may execute virtual reality engine 1126.

In various implementations, the above-described hardware and modules may be implemented on a single device or on multiple devices that can communicate with one another using wired or wireless connections. For example, in some implementations, some components or modules, such as GPUs, virtual reality engine 1126, and applications (e.g., tracking application), may be implemented on a console separate from the head-mounted display device. In some implementations, one console may be connected to or support more than one HMD.

In alternative configurations, different and/or additional components may be included in electronic system 1100. Similarly, functionality of one or more of the components can be distributed among the components in a manner different from the manner described above. For example, in some embodiments, electronic system 1100 may be modified to include other system environments, such as an AR system environment and/or an MR environment.

The methods, systems, and devices discussed above are examples. Various embodiments may omit, substitute, or add various procedures or components as appropriate. For

instance, in alternative configurations, the methods described may be performed in an order different from that described, and/or various stages may be added, omitted, and/or combined. Also, features described with respect to certain embodiments may be combined in various other embodiments. Different aspects and elements of the embodiments may be combined in a similar manner. Also, technology evolves and, thus, many of the elements are examples that do not limit the scope of the disclosure to those specific examples.

Specific details are given in the description to provide a thorough understanding of the embodiments. However, embodiments may be practiced without these specific details. For example, well-known circuits, processes, systems, structures, and techniques have been shown without unnecessary detail in order to avoid obscuring the embodiments. This description provides example embodiments only, and is not intended to limit the scope, applicability, or configuration of the invention. Rather, the preceding description of the embodiments will provide those skilled in the art with an enabling description for implementing various embodiments. Various changes may be made in the function and arrangement of elements without departing from the spirit and scope of the present disclosure.

Also, some embodiments were described as processes depicted as flow diagrams or block diagrams. Although each may describe the operations as a sequential process, many of the operations may be performed in parallel or concurrently. In addition, the order of the operations may be rearranged. A process may have additional steps not included in the figure. Furthermore, embodiments of the methods may be implemented by hardware, software, firmware, middleware, microcode, hardware description languages, or any combination thereof. When implemented in software, firmware, middleware, or microcode, the program code or code segments to perform the associated tasks may be stored in a computer-readable medium such as a storage medium. Processors may perform the associated tasks.

It will be apparent to those skilled in the art that substantial variations may be made in accordance with specific requirements. For example, customized or special-purpose hardware might also be used, and/or particular elements might be implemented in hardware, software (including portable software, such as applets, etc.), or both. Further, connection to other computing devices such as network input/output devices may be employed.

With reference to the appended figures, components that can include memory can include non-transitory machine-readable media. The term "machine-readable medium" and "computer-readable medium," as used herein, refer to any storage medium that participates in providing data that causes a machine to operate in a specific fashion. In embodiments provided hereinabove, various machine-readable media might be involved in providing instructions/code to processing units and/or other device(s) for execution. Additionally or alternatively, the machine-readable media might be used to store and/or carry such instructions/code. In many implementations, a computer-readable medium is a physical and/or tangible storage medium. Such a medium may take many forms, including, but not limited to, non-volatile media, volatile media, and transmission media. Common forms of computer-readable media include, for example, magnetic and/or optical media such as compact disk (CD) or digital versatile disk (DVD), punch cards, paper tape, any other physical medium with patterns of holes, a RAM, a programmable read-only memory (PROM), an erasable programmable read-only memory (EPROM), a FLASH-

EPROM, any other memory chip or cartridge, a carrier wave as described hereinafter, or any other medium from which a computer can read instructions and/or code. A computer program product may include code and/or machine-executable instructions that may represent a procedure, a function, a subprogram, a program, a routine, an application (App), a subroutine, a module, a software package, a class, or any combination of instructions, data structures, or program statements.

Those of skill in the art will appreciate that information and signals used to communicate the messages described herein may be represented using any of a variety of different technologies and techniques. For example, data, instructions, commands, information, signals, bits, symbols, and chips that may be referenced throughout the above description may be represented by voltages, currents, electromagnetic waves, magnetic fields or particles, optical fields or particles, or any combination thereof.

Terms, “and” and “or” as used herein, may include a variety of meanings that are also expected to depend at least in part upon the context in which such terms are used. Typically, “or” if used to associate a list, such as A, B, or C, is intended to mean A, B, and C, here used in the inclusive sense, as well as A, B, or C, here used in the exclusive sense. In addition, the term “one or more” as used herein may be used to describe any feature, structure, or characteristic in the singular or may be used to describe some combination of features, structures, or characteristics. However, it should be noted that this is merely an illustrative example and claimed subject matter is not limited to this example. Furthermore, the term “at least one of” if used to associate a list, such as A, B, or C, can be interpreted to mean any combination of A, B, and/or C, such as A, AB, AC, BC, AA, ABC, AAB, AABBBCC, etc.

Further, while certain embodiments have been described using a particular combination of hardware and software, it should be recognized that other combinations of hardware and software are also possible. Certain embodiments may be implemented only in hardware, or only in software, or using combinations thereof. In one example, software may be implemented with a computer program product containing computer program code or instructions executable by one or more processors for performing any or all of the steps, operations, or processes described in this disclosure, where the computer program may be stored on a non-transitory computer readable medium. The various processes described herein can be implemented on the same processor or different processors in any combination.

Where devices, systems, components or modules are described as being configured to perform certain operations or functions, such configuration can be accomplished, for example, by designing electronic circuits to perform the operation, by programming programmable electronic circuits (such as microprocessors) to perform the operation such as by executing computer instructions or code, or processors or cores programmed to execute code or instructions stored on a non-transitory memory medium, or any combination thereof. Processes can communicate using a variety of techniques, including, but not limited to, conventional techniques for inter-process communications, and different pairs of processes may use different techniques, or the same pair of processes may use different techniques at different times.

The specification and drawings are, accordingly, to be regarded in an illustrative rather than a restrictive sense. It will, however, be evident that additions, subtractions, deletions, and other modifications and changes may be made

thereunto without departing from the broader spirit and scope as set forth in the claims. Thus, although specific embodiments have been described, these are not intended to be limiting. Various modifications and equivalents are within the scope of the following claims.

What is claimed is:

1. An illuminator for eye tracking comprising:

a substrate transparent to visible light and configured to be placed in front of an eye of a user;

a plurality of light sources positioned sparsely in or on a surface of the substrate and configured to emit infrared light for eye tracking; and

a plurality of beam diverting components that are spaced apart from each other and are placed sparsely on the substrate or the plurality of light sources in a field of view of the eye of the user, wherein:

each beam diverting component of the plurality of beam diverting components corresponds to one respective light source of the plurality of light sources, and is configured to direct the infrared light from the respective light source of the plurality of light sources to a different respective direction toward the eye of the user, and

for each light source of the plurality of light sources: the light source is configured to be positioned within the field of view of the eye of the user, and a maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 nm.

2. The illuminator of claim 1, wherein, for each light source of the plurality of light sources, an angle of an emission cone of the infrared light from the light source is less than 30°.

3. The illuminator of claim 1, wherein each beam diverting component of the plurality of beam diverting components includes a micro-prism, an inverse micro-prism, a grating, or an inclined plane.

4. The illuminator of claim 1, further comprising an encapsulation layer that surrounds each light source of the plurality of light sources, wherein a refractive index of the encapsulation layer matches a refractive index of the substrate.

5. The illuminator of claim 1, wherein:

the substrate comprises a conductive trace, and for each light source of the plurality of light sources, the light source comprises an electrode that is electrically connected to the conductive trace.

6. The illuminator of claim 1, further comprising a metal-loaded conductive adhesive that bonds each light source of the plurality of light sources to the substrate.

7. The illuminator of claim 1, wherein the surface of the substrate is flat.

8. The illuminator of claim 1, wherein the substrate comprises at least one of glass, quartz, plastic, polymer, ceramic, or crystal.

9. The illuminator of claim 1, wherein each beam diverting component of the plurality of beam diverting components is configured to direct the infrared light from the respective light source of the plurality of light sources to a different respective area of the eye of the user.

10. The illuminator of claim 1, wherein:

each beam diverting component of the plurality of beam diverting components includes an inclined plane; and each light source of the plurality of light sources is positioned on the inclined plane of a respective beam diverting component.

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11. An eye-tracking unit for a near-eye display device, the eye-tracking unit comprising:

- a substrate transparent to visible light and configured to be placed in front of an eye of a user;
- a plurality of light sources positioned sparsely in or on a surface of the substrate and configured to emit infrared light for eye tracking;
- a plurality of beam diverting components that are spaced apart from each other and are placed sparsely on the substrate or the plurality of light sources in a field of view of the eye of the user, wherein each beam diverting component of the plurality of beam diverting components corresponds to one respective light source of the plurality of light sources, and is configured to direct the infrared light from the respective light source of the plurality of light sources to a different respective direction toward the eye of the user; and
- a camera configured to receive the infrared light from the plurality of light sources that is reflected by the eye of the user,

wherein, for each light source of the plurality of light sources:

- the light source is configured to be positioned within the field of view of the eye of the user, and
- a maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 μm .

12. The eye-tracking unit of claim 11, wherein, for each light source of the plurality of light sources, an angle of an emission cone of the infrared light from the light source is less than 30°.

13. The eye-tracking unit of claim 11, wherein each beam diverting component of the plurality of beam diverting components includes a micro-prism, an inverse micro-prism, a grating, or an inclined plane.

14. The eye-tracking unit of claim 11, further comprising an encapsulation layer that surrounds each light source of the plurality of light sources, wherein a refractive index of the encapsulation layer matches a refractive index of the substrate.

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15. The eye-tracking unit of claim 11, wherein: the substrate comprises a conductive trace, and for each light source of the plurality of light sources, the light source comprises an electrode that is electrically connected to the conductive trace.

16. The eye-tracking unit of claim 11, further comprising a metal-loaded conductive adhesive that bonds each light source of the plurality of light sources to the substrate.

17. The eye-tracking unit of claim 11, wherein the surface of the substrate is flat.

18. The eye-tracking unit of claim 11, wherein the substrate comprises at least one of glass, quartz, plastic, polymer, ceramic, or crystal.

19. A method of tracking an eye of a user of a near-eye display, the method comprising:

- emitting infrared light by a plurality of light sources positioned sparsely on a transparent substrate within a field of view of the eye of the user, wherein, for each light source of the plurality of light sources, a maximum dimension of the light source in a plane parallel to an emission surface of the light source is less than 500 μm ;
- directing, by each beam diverting component of a plurality of beam diverting components that are spaced apart from each other and are placed sparsely on the transparent substrate or the plurality of light sources in a field of view of the eye of the user, the infrared light from a respective light source of the plurality of light sources to a different respective direction toward the eye of the user, wherein each beam diverting component of the plurality of beam diverting components corresponds to one light source of the plurality of light sources; and
- receiving, by a camera, the infrared light from the plurality of light sources and reflected by the eye of the user.

20. The method of claim 19, further comprising: generating, by the camera using the received infrared light reflected by the eye of the user, an image frame comprising an image of the plurality of light sources reflected by the eye of the user.

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